First Measurement of Interference Fragmentation Functions at

BELLE

and Outlook on the Measurement of local P-odd effects in Fragmentation

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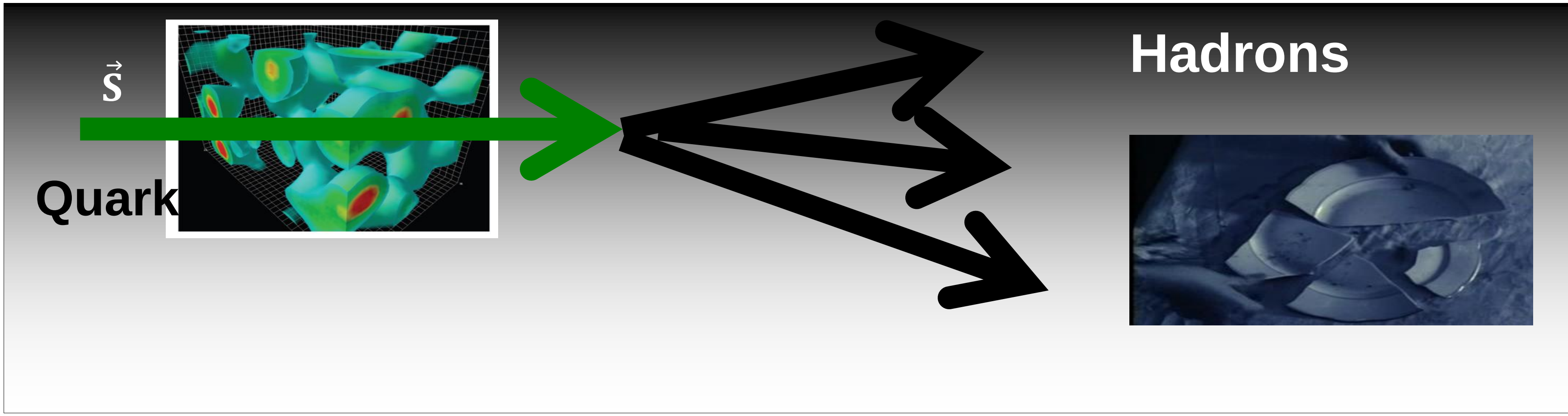
INDIANA UNIVERSITY

arXiv:1104.2425

Submitted to PRL

Motivation & Outline



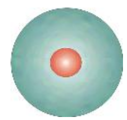
- Transverse spin dependent fragmentation functions are necessary to extract quark transversity
- Measurement of TSD FFs at BELLE
- Plans to measure P-odd FFs
- Outlook

Parton Distribution Functions

The three leading order, collinear PDFs

$q(x)$

$f_1^q\,(x)$



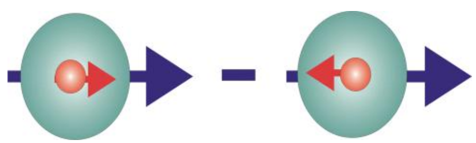
unpolarized PDF

quark with momentum $x = p_{quark}/p_{proton}$ in a nucleon

well known – unpolarized DIS

$\Delta q(x)$

$g_1^q(x)$



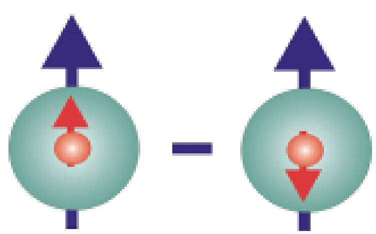
helicity PDF

quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon

known – polarized DIS

$\Delta_T q(x)$

$h_1^q(x)$



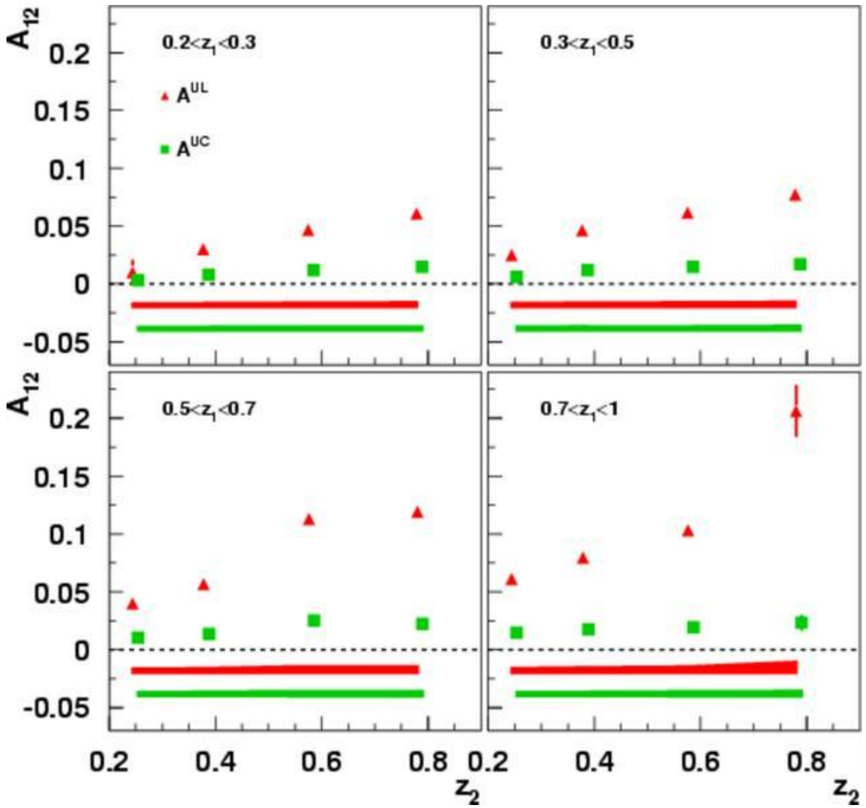
transversity PDF

quark with spin parallel to the nucleon spin in a transversely polarized nucleon

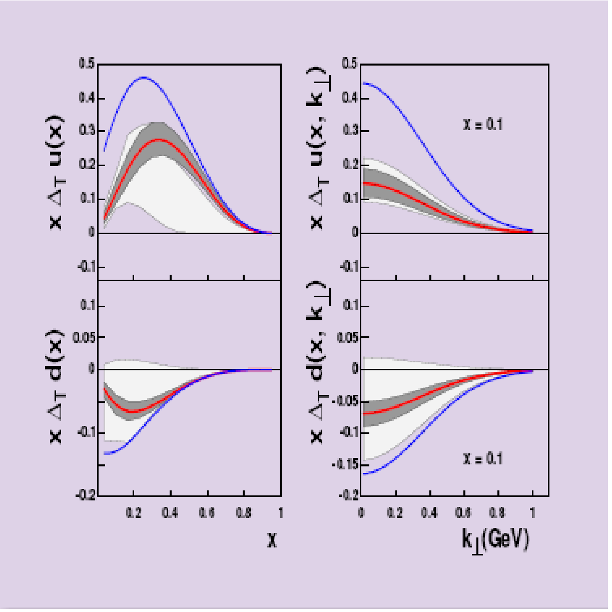
chiral odd, poorly known

Cannot be measured inclusively

Belle Fragmentation Function Measurement makes first Extraction of Transversity possible!



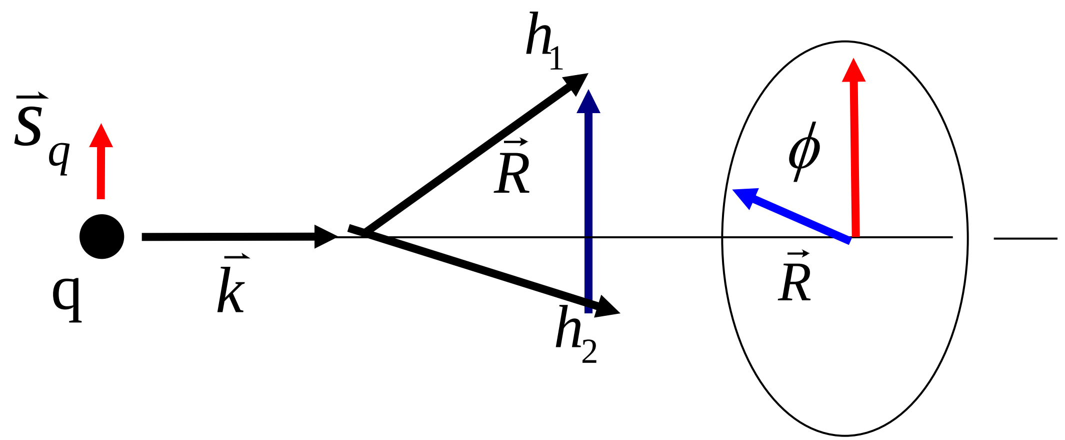
Together with HERMES, COMPASS First, still model dependent transversity Extraction :



Alexei Prokudin, DIS2008, update of Anselmino et al: hep-ex 0701006

Belle 547 fb^{-1} data set (Phys.Rev.D78:032011,2008.)

Interference FF in Quark Fragmentation



$\vec{k}$	: quark momentum
$\vec{s}_q$	:quark spin
$\vec{R}$	: momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$
$\vec{R}_T$	transverse hadron momentum difference
z_{pair}	$= E_{pair}/E_q$
$=2E_{pair}/\sqrt{s}$	: relative hadron pair momentum
m	: hadron pair invariant mass

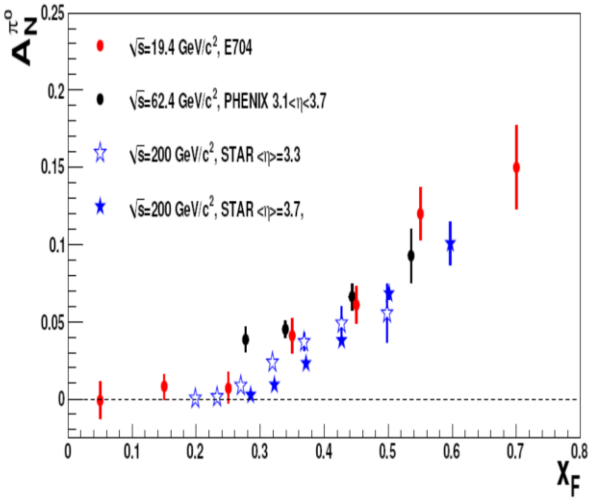
Interference Fragmentation Function:
Fragmentation of a transversely polarized quark *q* into two spin-less hadron *h1, h2* carries an azimuthal dependence:

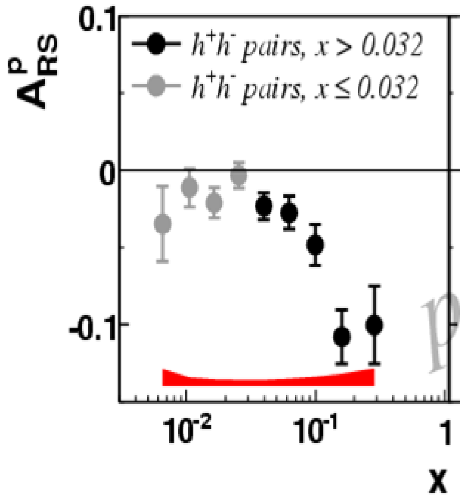
$$\propto \left(\vec{k} \times \vec{R}_T\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

Interference FF vs. Collins Effect

- Independent Measurement
- Favorable in proton-proton collisions: no other contributions (no Sivers): Disentangle sources of large transverse spin asymmetries
- Transverse momentum is integrated
  – Collinear factorization
- No assumption about k_t in evolution
- evolution known, collinear scheme can be used
- Universal function: directly applicable to semi-inclusive DIS and pp
- First experimental results from HERMES, COMPASS, PHENIX and now Belle





No jet reconstruction necessary, better systematics

Spin Dependent FF in e^+e^- : Need Correlation between Hemispheres !

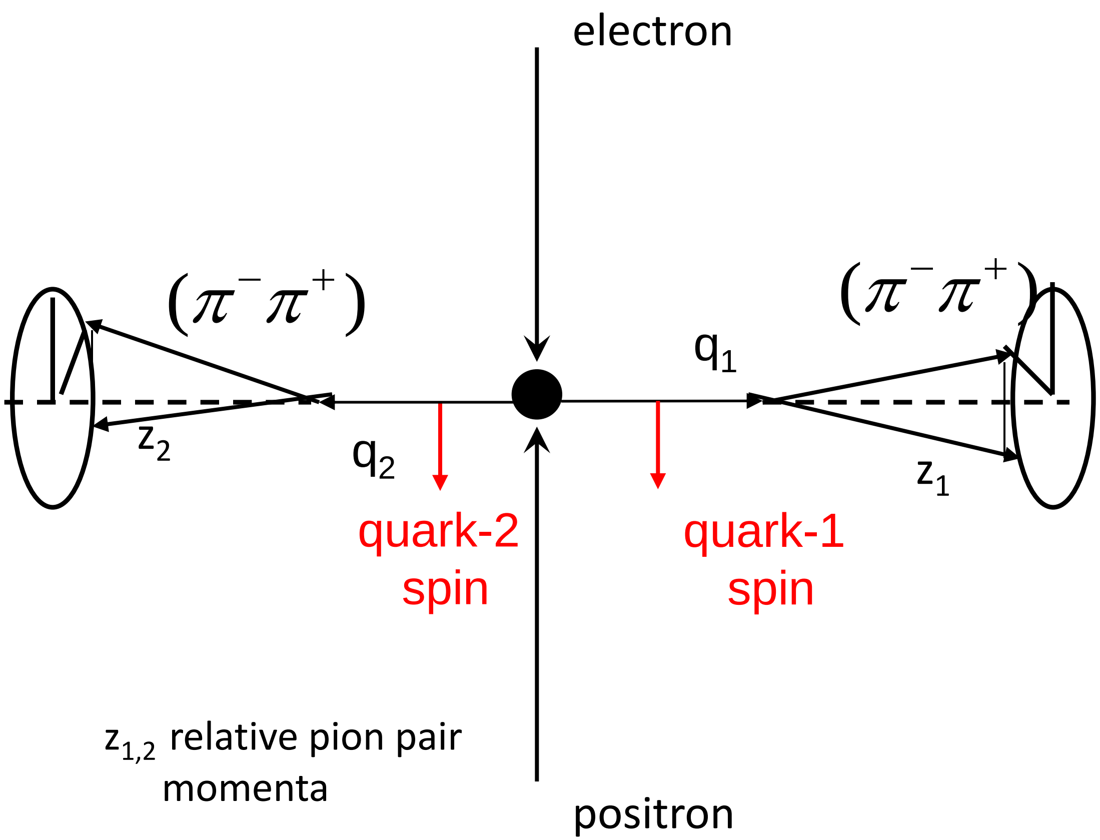
- Quark spin direction unknown: measurement of Interference Fragmentation function in one hemisphere is not possible

  sin φ modulation will average out.

- Correlation between two hemispheres with $\sin\varphi_{Ri}$ single spin asymmetries results in $\cos(\varphi_{R1}+\varphi_{R2})$ modulation of the observed di-hadron yield.

Measurement of azimuthal correlations for di-pion pairs around the jet axis in two-jet events!

Measuring di-Hadron Correlations In e^+e^- Annihilation into Quarks



$z_{1,2}$ relative pion pair momenta

Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

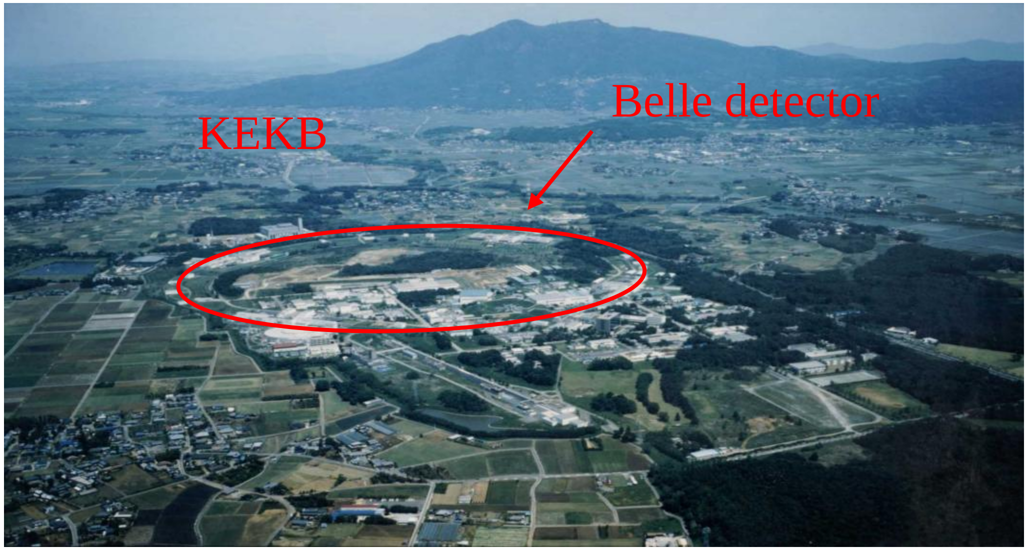
Experimental requirements:

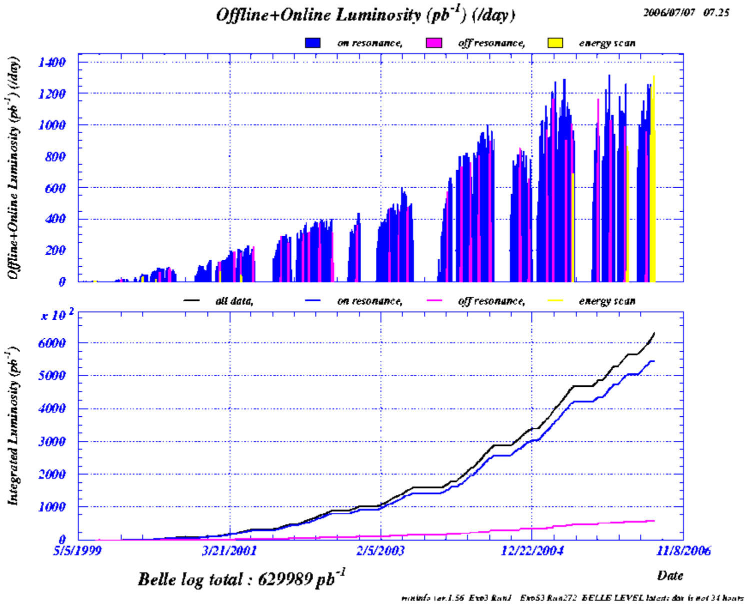
- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector
- Observable: $\cos(\varphi_{R1}+\varphi_{R2})$

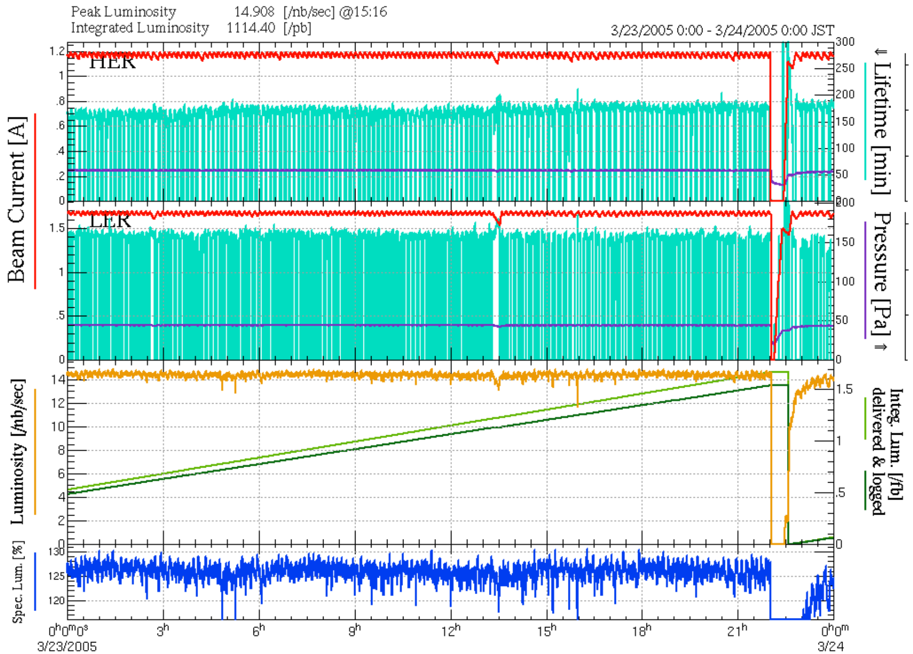
modulation measures $H_1^{\angle}\overline{H}_1^{\angle}$

KEKB: L>2.11 x $10^{34}cm^{-2}s^{-1}$!!

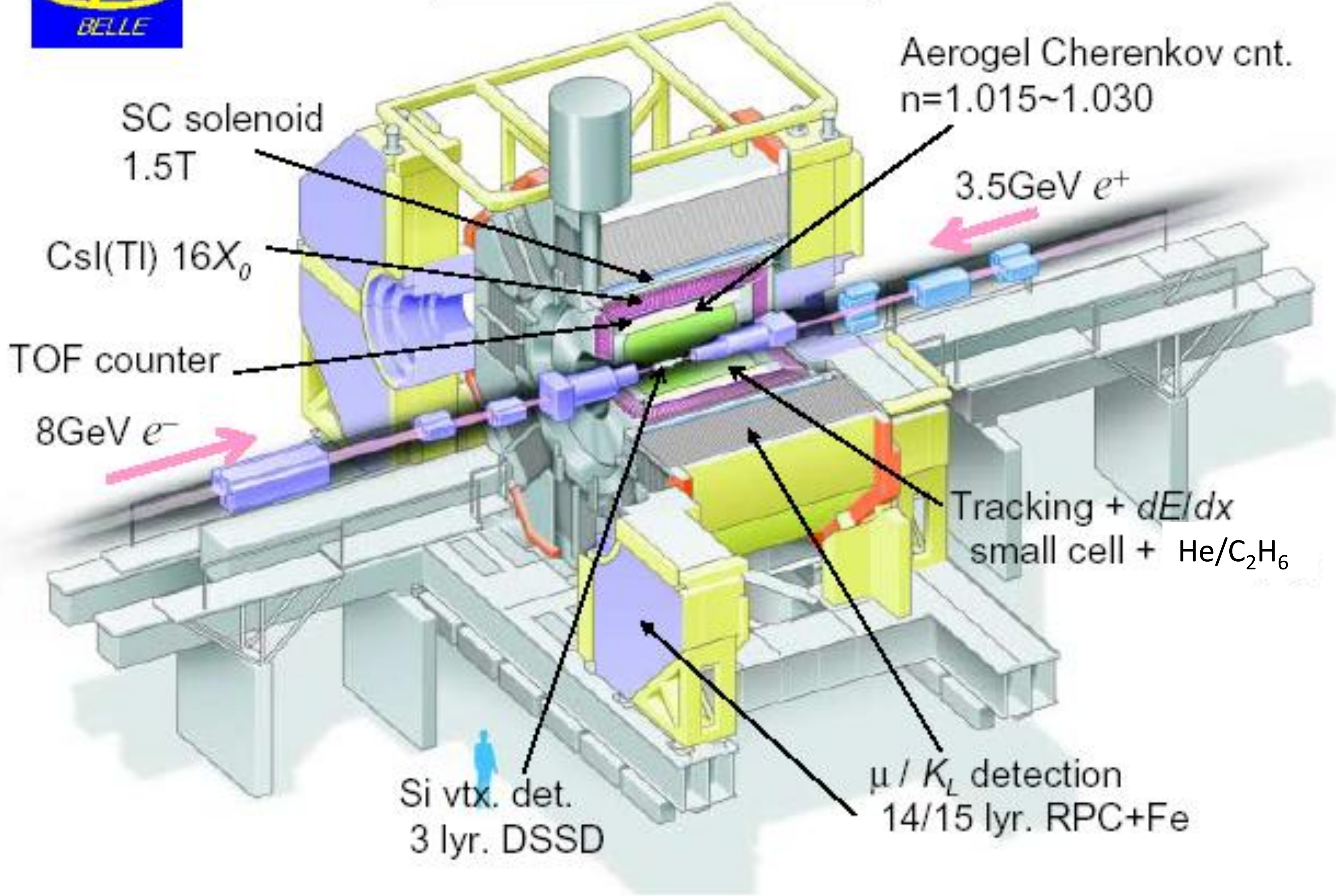
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV ($\Upsilon(4S)$)
- $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)
- Integrated Luminosity: > 1000 fb^{-1}
- >70 fb^{-1} => continuum





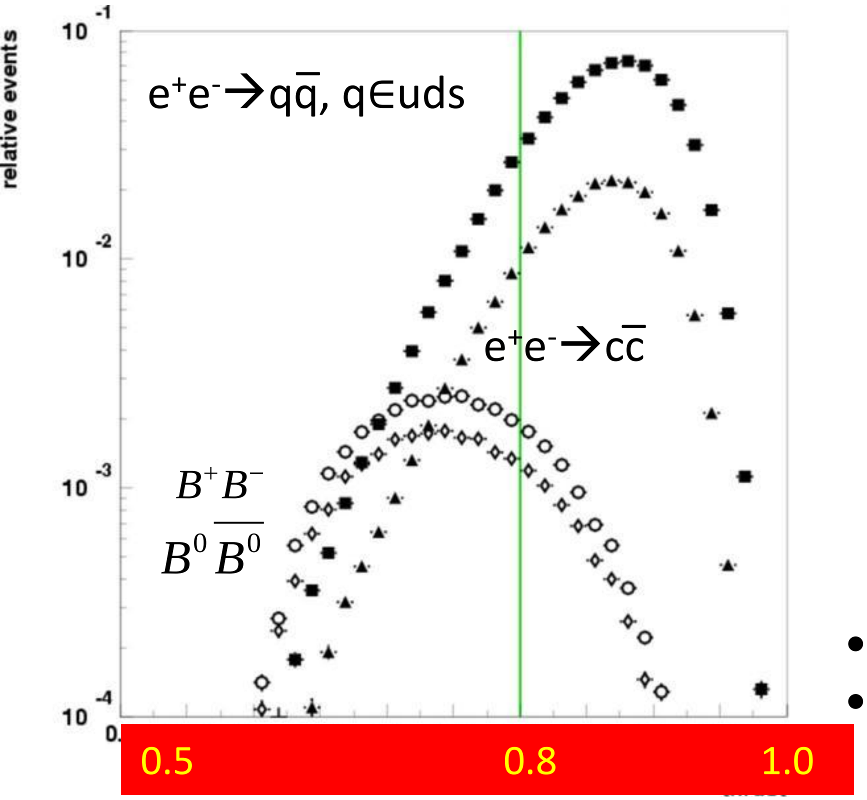


Belle Detector

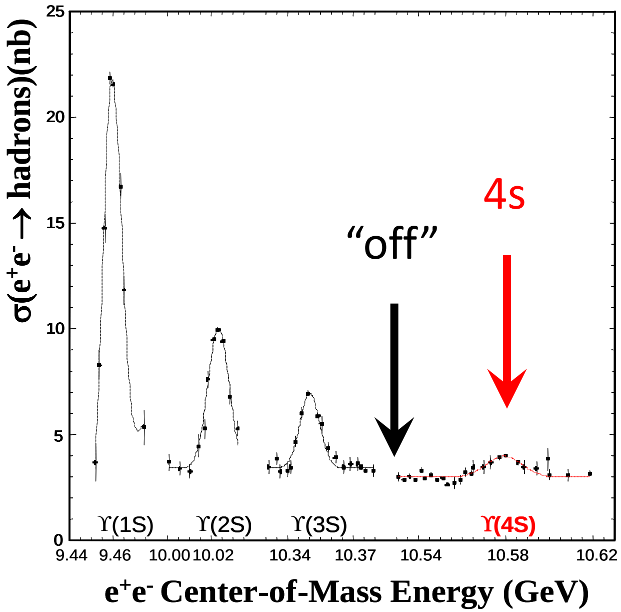


Large acceptance, good tracking and particle identification!

Measuring Light Quark Fragmentation Functions on the $\Upsilon(4S)$ Resonance



$$Thrust:\ T = \frac{\sum_i |p_i \cdot \hat{n}|}{\sum_i |p_i|}$$



- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under Υ (4S) resonance
- 73 fb^{-1} ➔ 662 fb^{-1}

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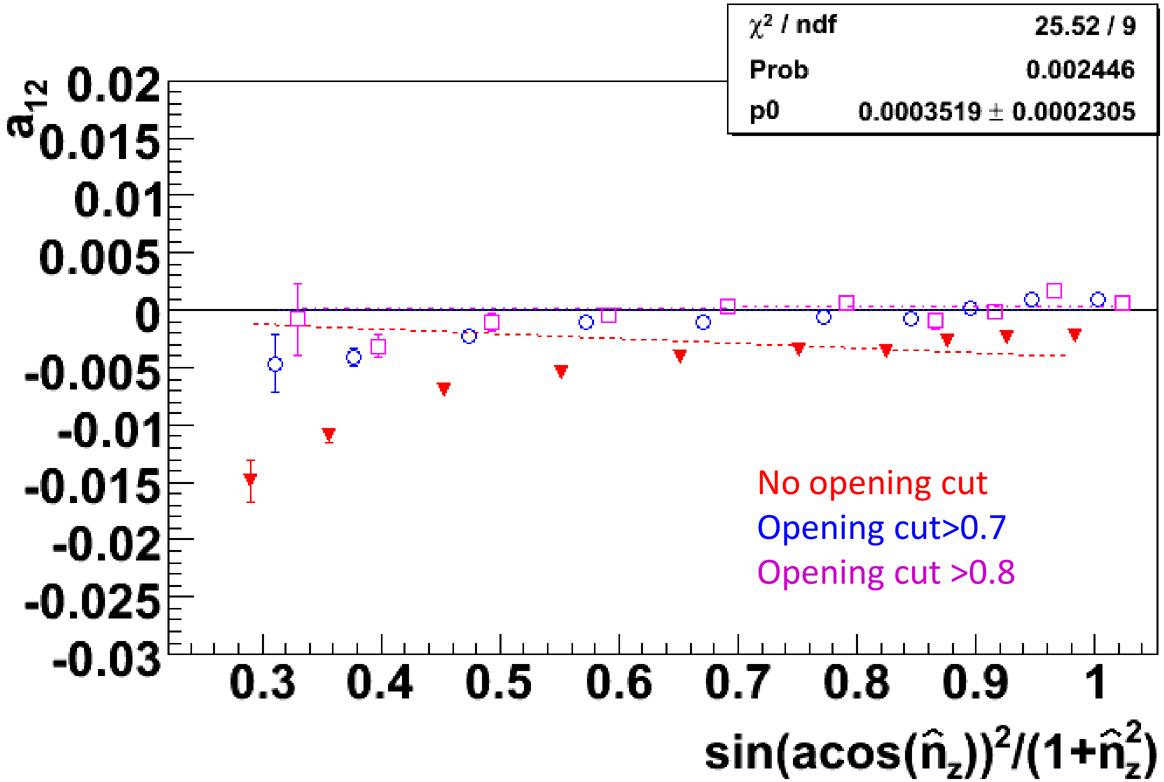
Cuts and Binning

- Similar to Collins analysis, full off-resonance and on-resonance data (7-55): ~73 fb^{-1} + 588 fb^{-1}
- Visible energy >7GeV
- PID: Purities in for di-pion pairs > 90%
- Same Hemisphere cut within pair ($\pi^+\pi^-$), opposite hemisphere between pairs
- All 4 hadrons in barrel region: -0.6 < cos (θ) <0.9
- Thrust axis in central area: cosine of thrust axis around beam <0.75
- Thrust > 0.8
- $z_{had1,had2}$>0.1
- $z_1 = z_{had1}+z_{had2}$ and z_2 in 9x9 bins
- $m_{\pi\pi 1}$ and $m_{\pi\pi 2}$ in 8x8 bins: [0.25 - 2.0] GeV
- New: Mixed binning

Zero tests: MC



- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
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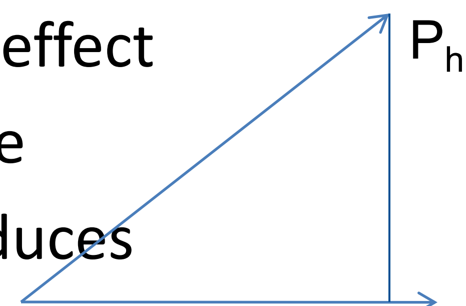

$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P, n)$$

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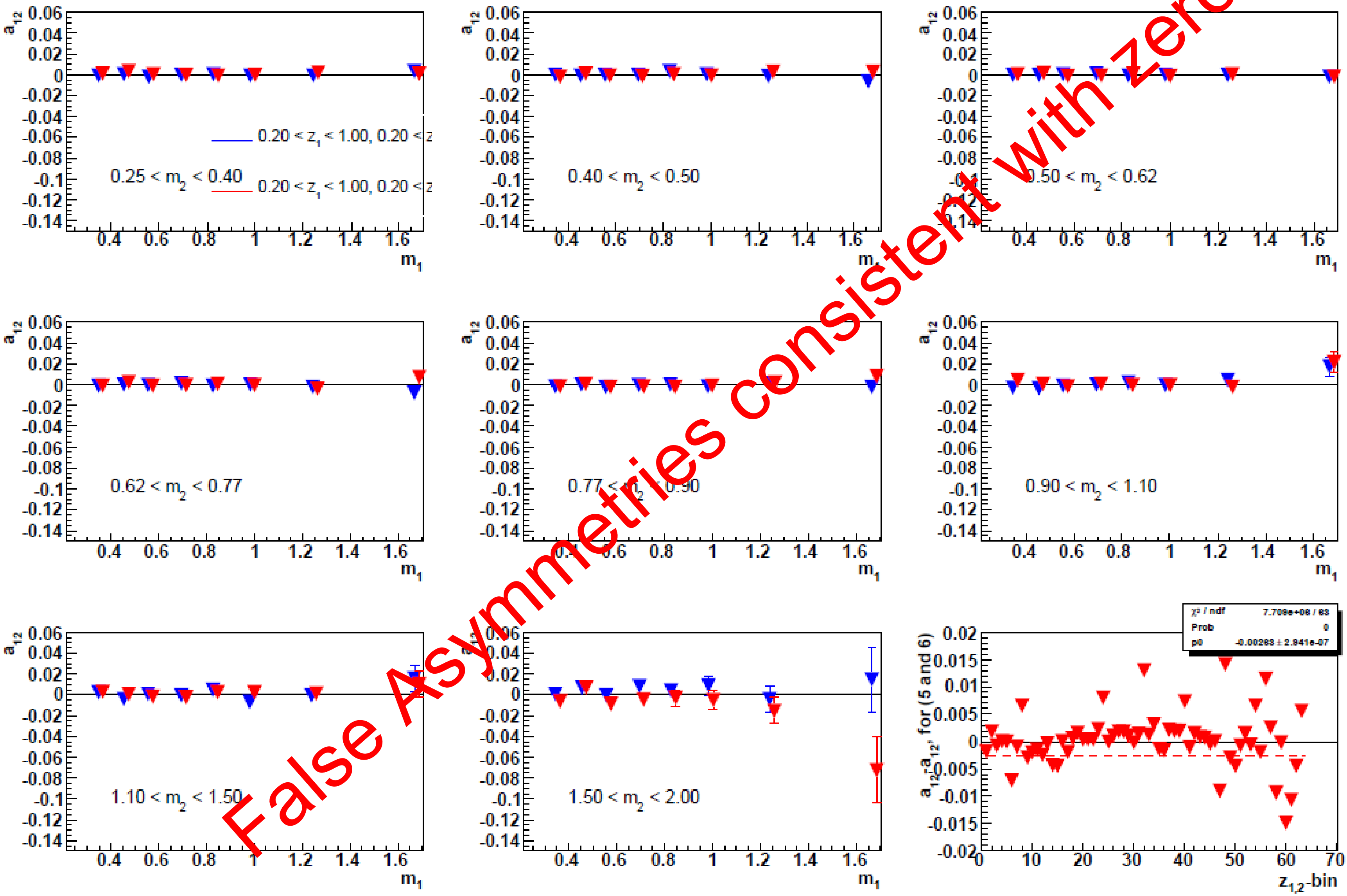
Zero tests: Mixed Events

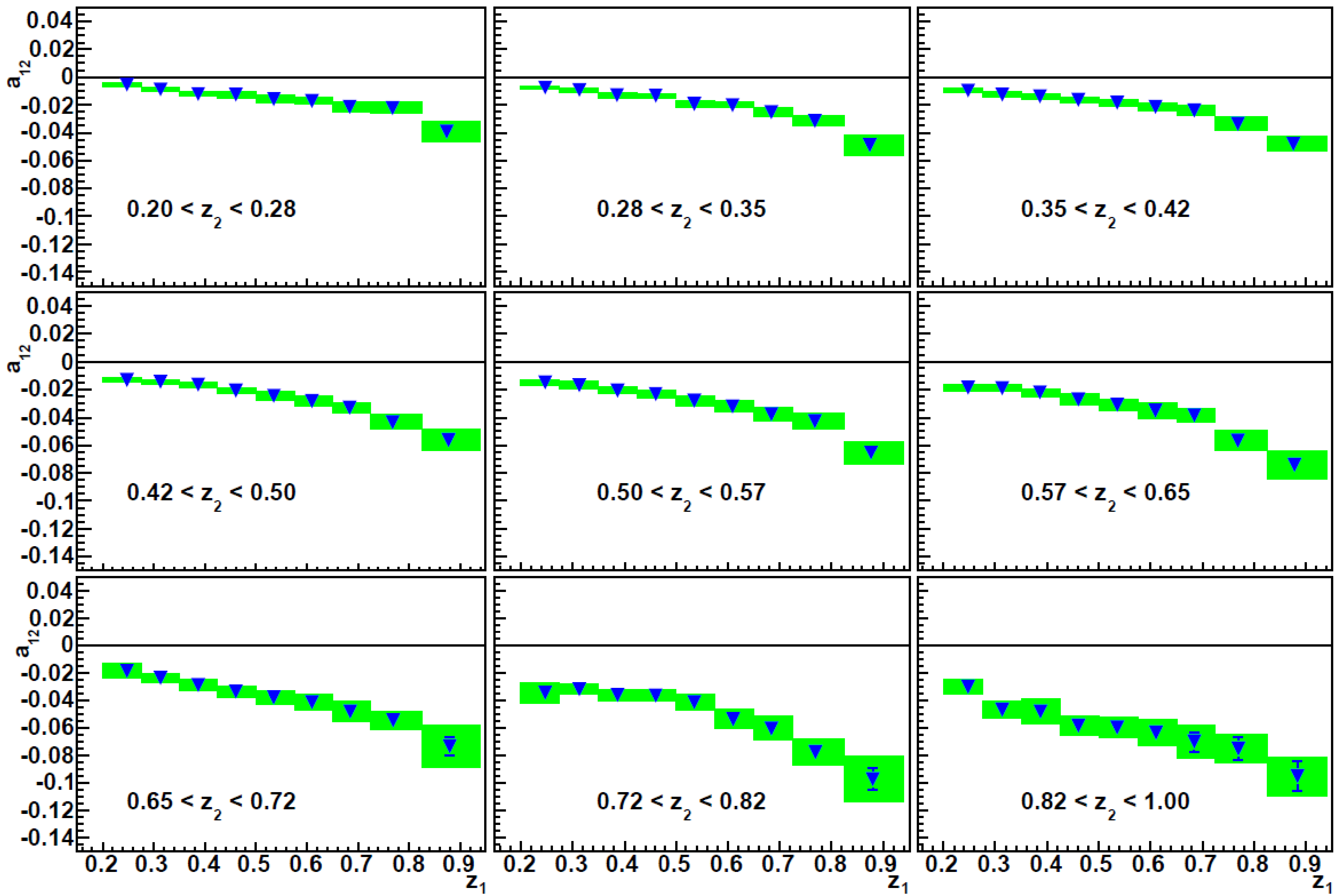


False Asymmetries consistent with zero

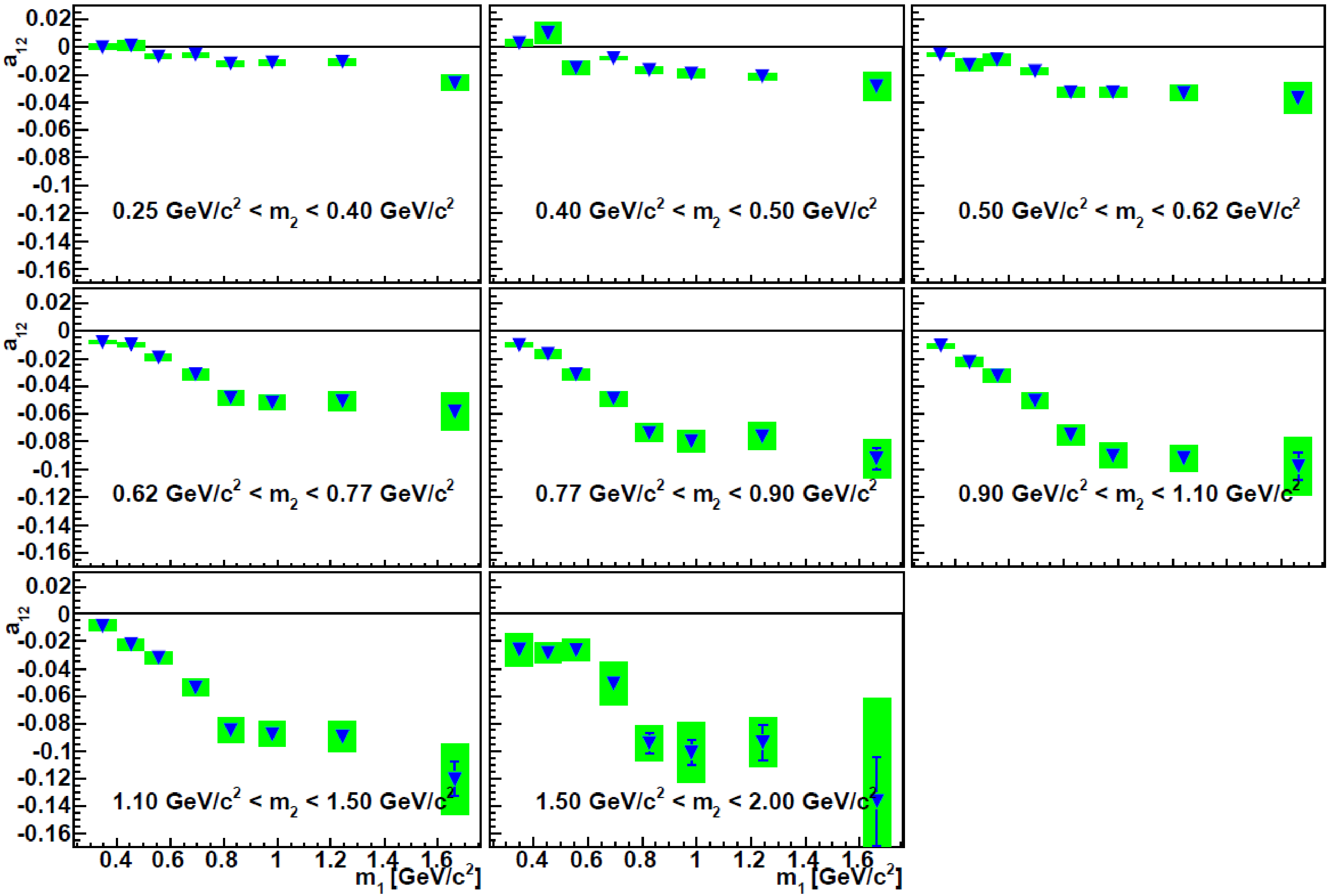
Systematic Errors

- Dominant:
  - MC asymmetry + its statistical error (up to % level)
- Smaller contributions:
  - PID: per mille level
  - higher moments: sub per mille level
  - axis smearing
  - mixed asymmetries: per mille level

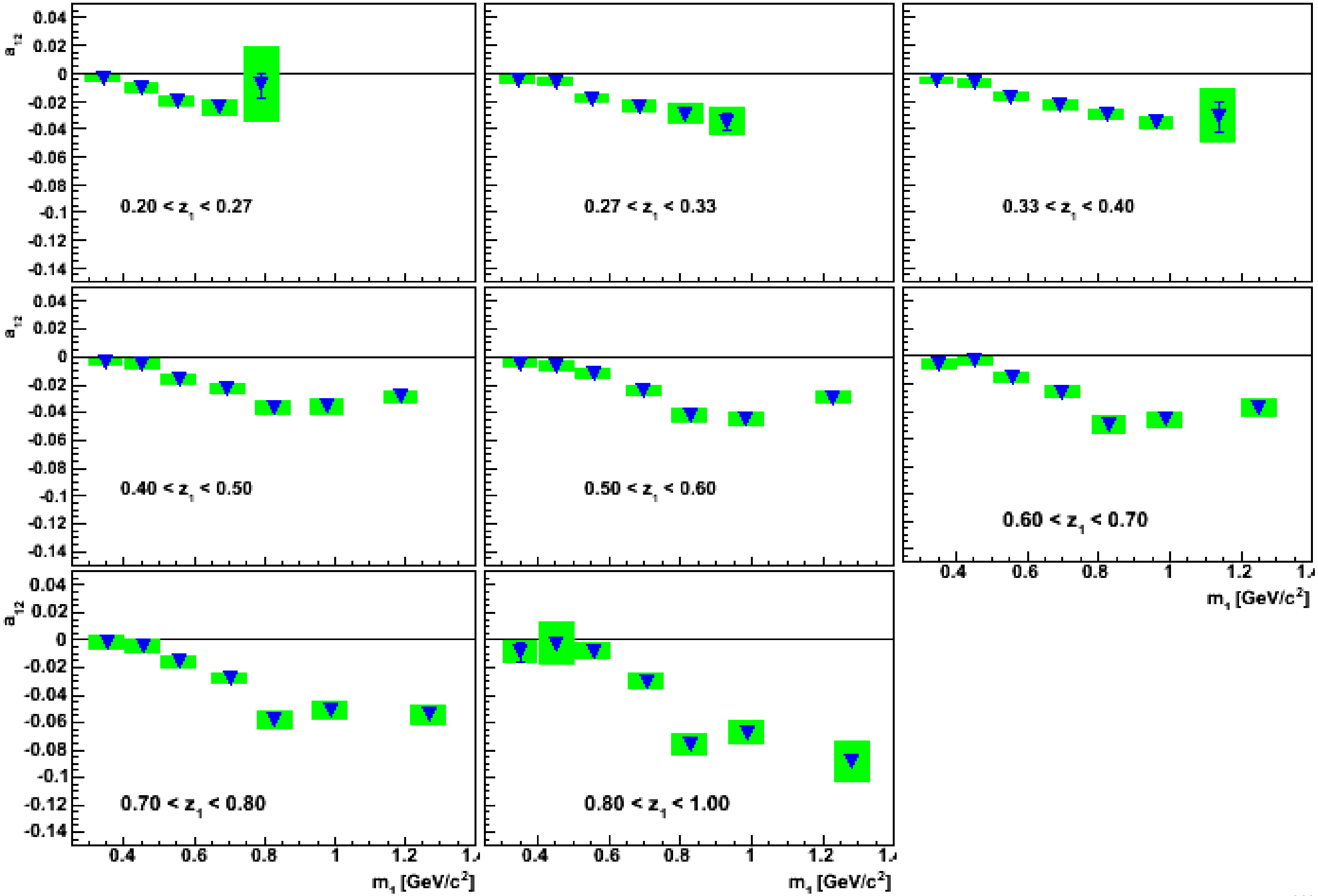
Results incl. sys. errors: (z_1x z_2) Binning



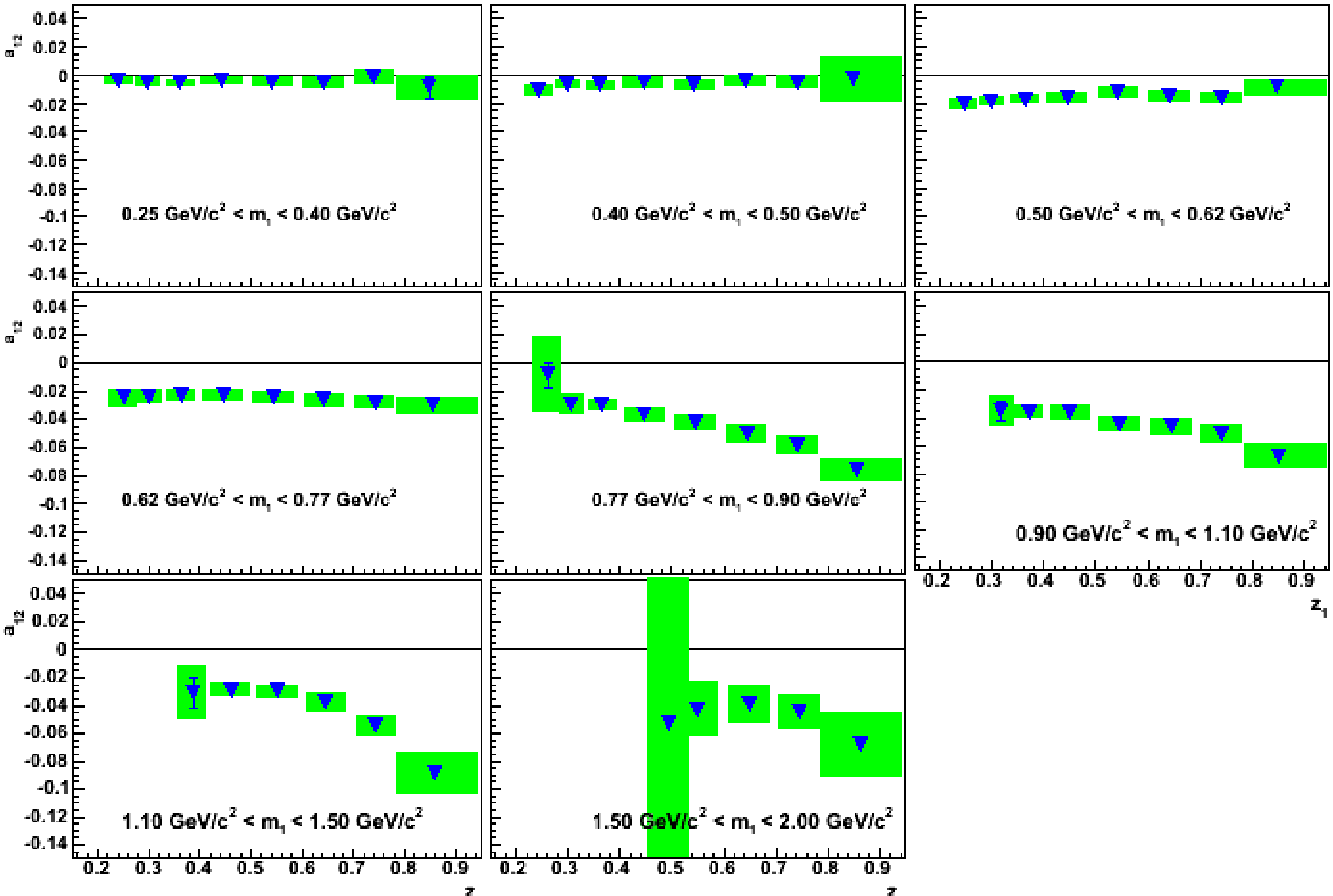
$(m_1 x\ m_2)$ Binning



(z_1x m_1) Binning

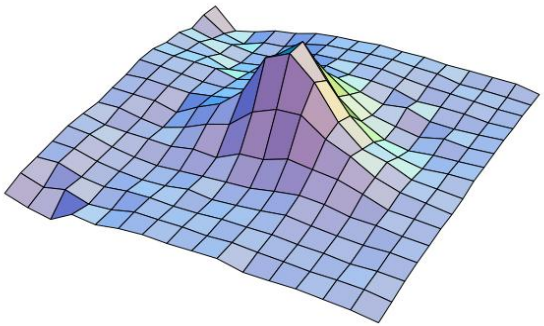


(m_1x z_1) Binning

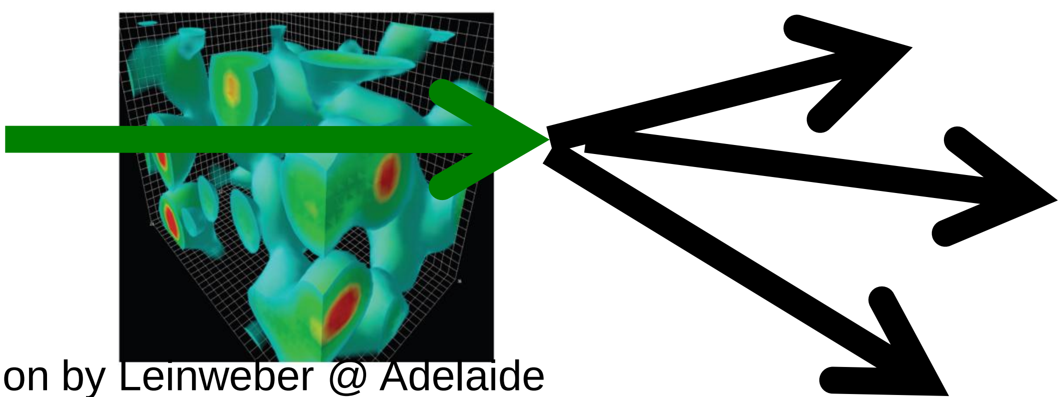


Accessing QCD vacuum fluctuations in Quark Fragmentation

- Transitions between QCD vacuum ground states by non-perturbative gluon configurations:
- On microscopic scale quarks coupling to these leads to P-odd effects: Net Chirality is picked up in transition
  - First results at STAR and PHENIX
  - Planned measurements in Belle: needed as a ‘tie breaker’
  - Model Calculations predict 2% effect

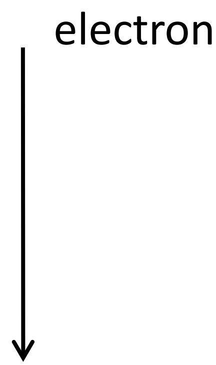


- Access to nonperturpative properties of QCD (vacuum structure)
- First observation of Sphaleron/Instanton induced processes: non-perturbative topological objects
- In EW sector similar transitions are needed for Baryogenesis



Simulation by Leinweber @ Adelaide

Event Topology in e+ e-



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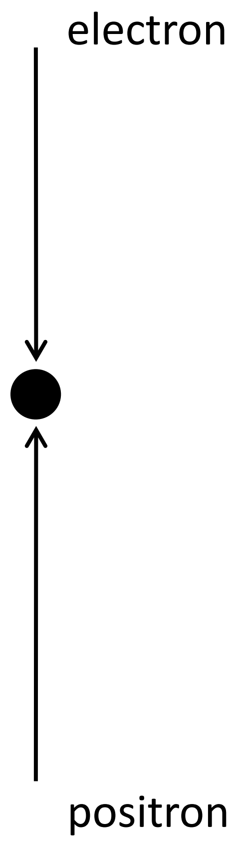

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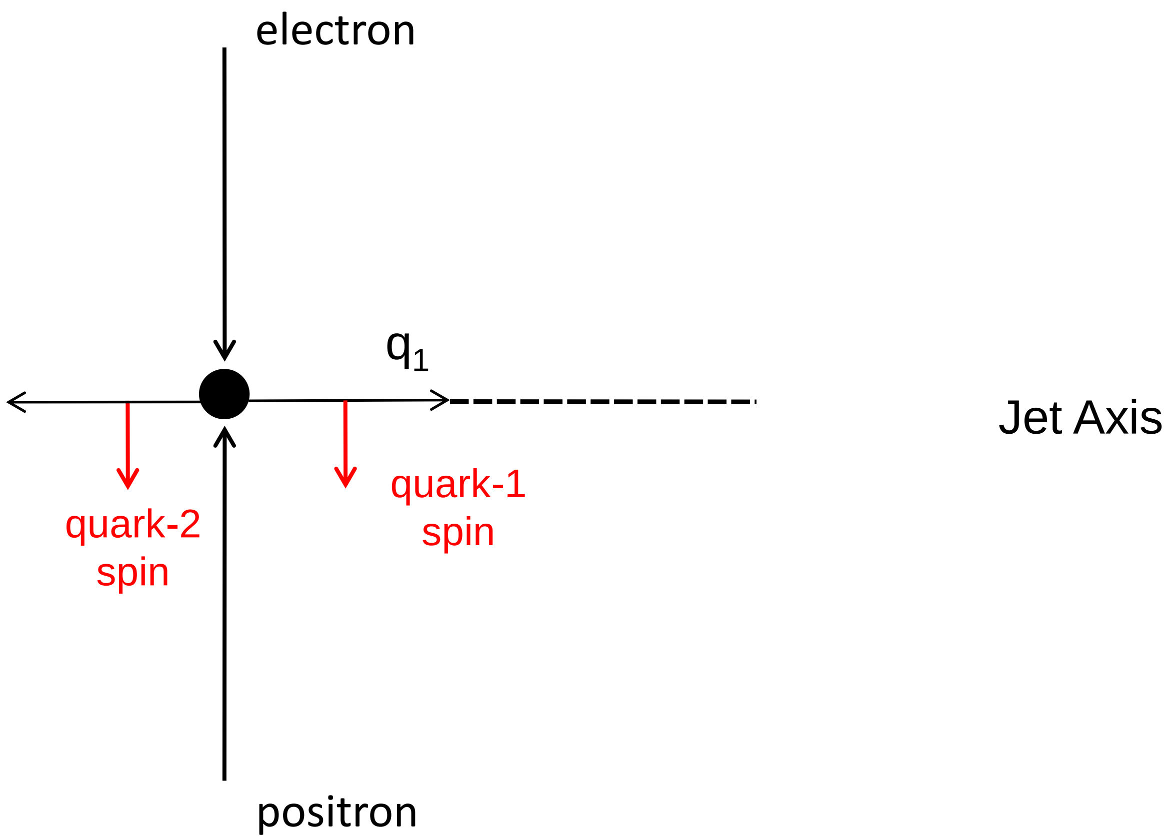

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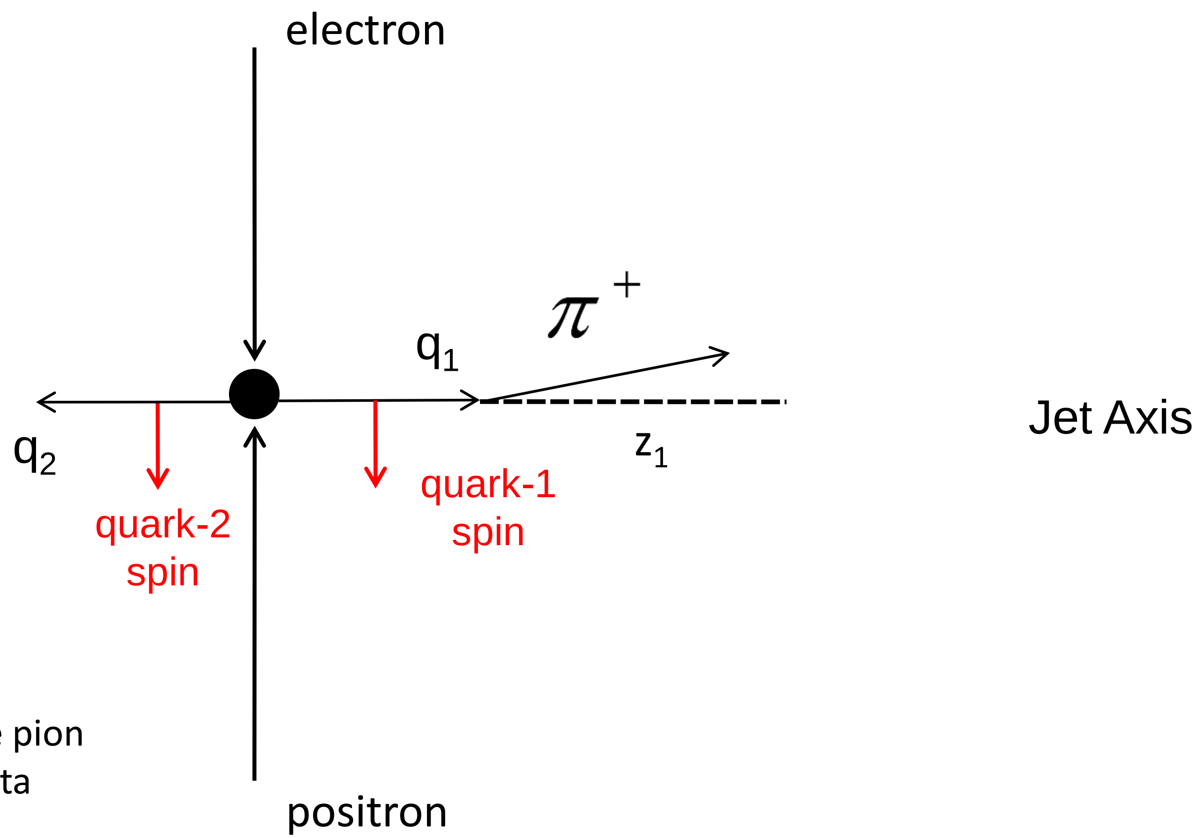
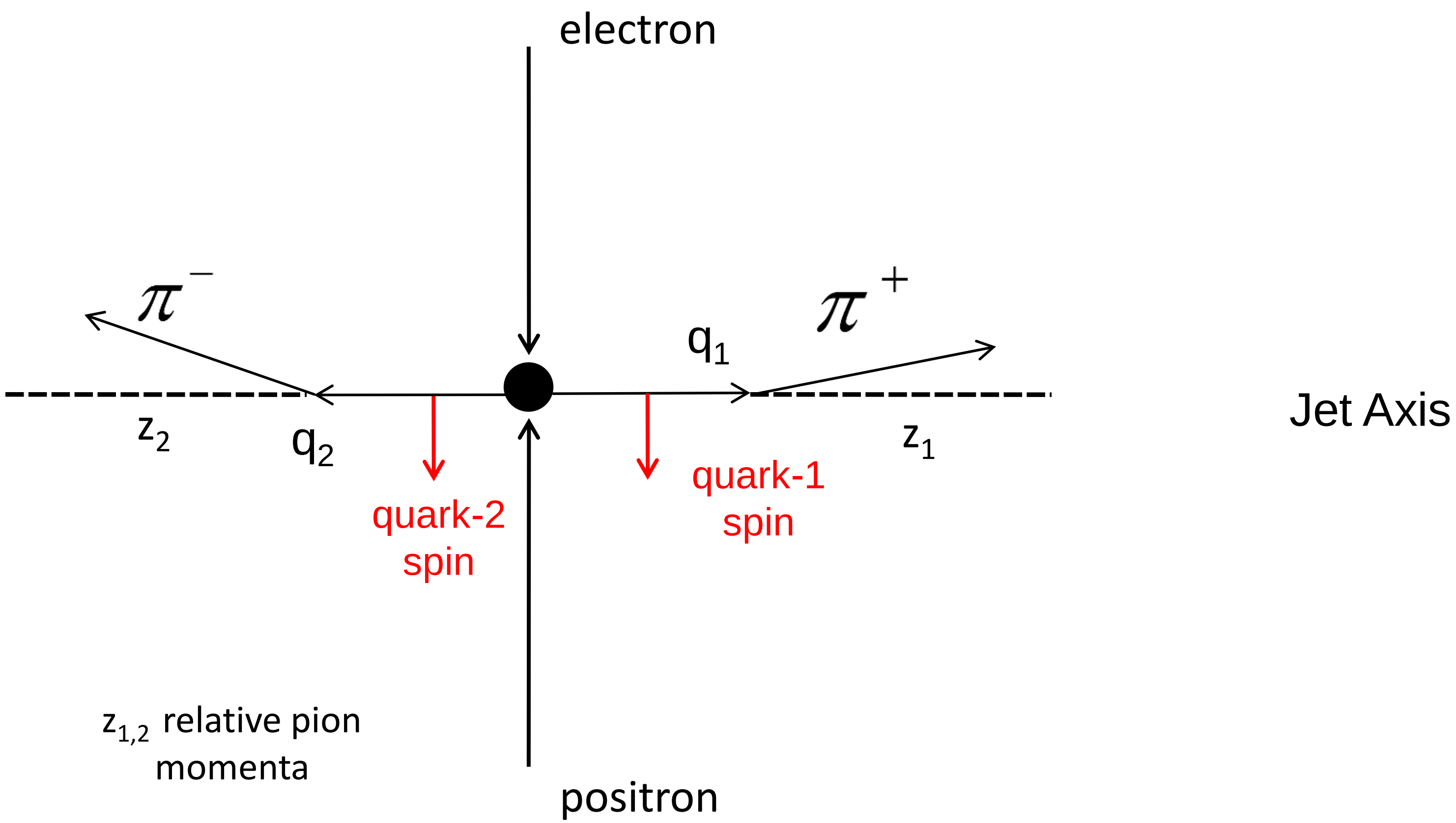


$z_{1,2}$ relative pion momenta

Event Topology in e+ e-



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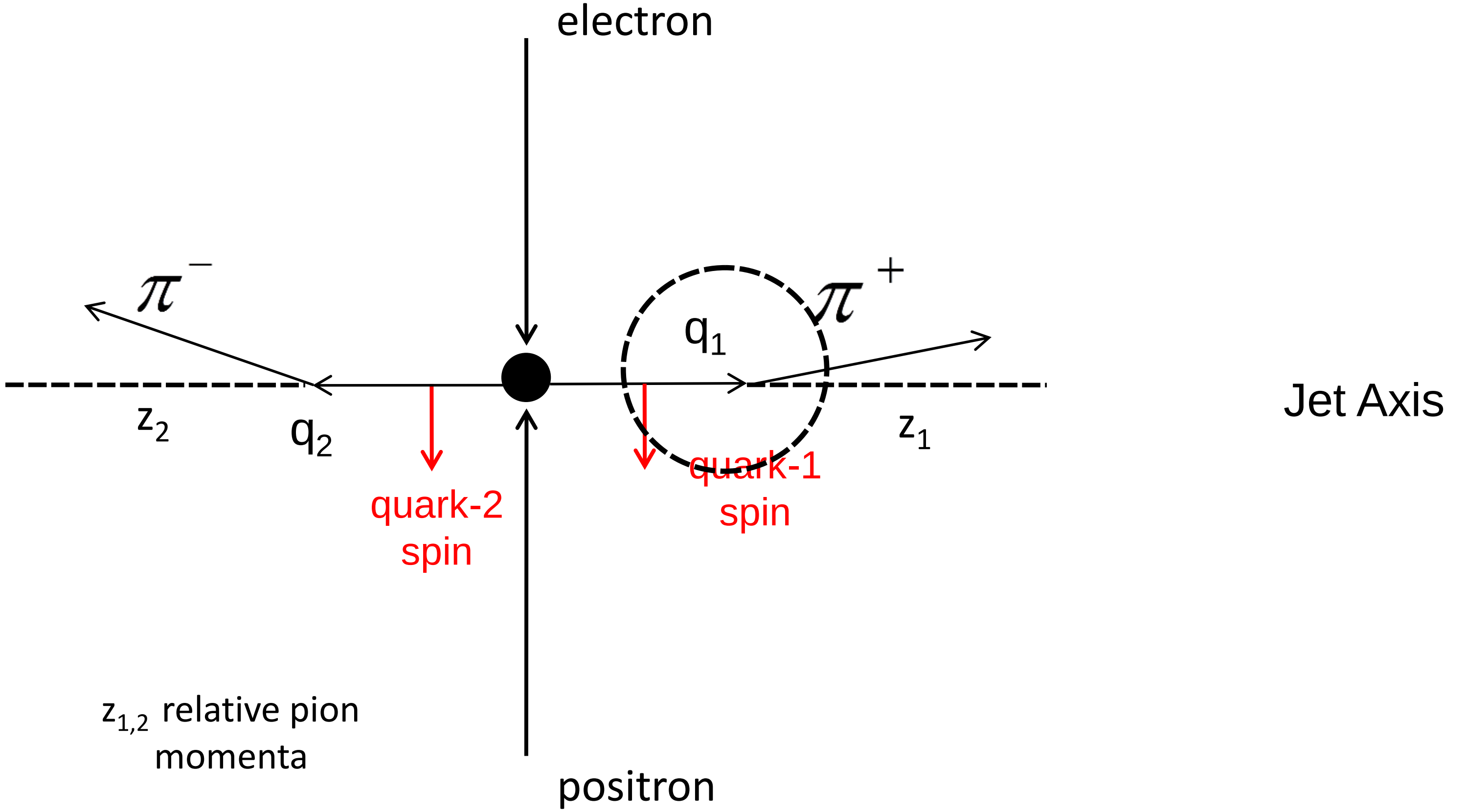
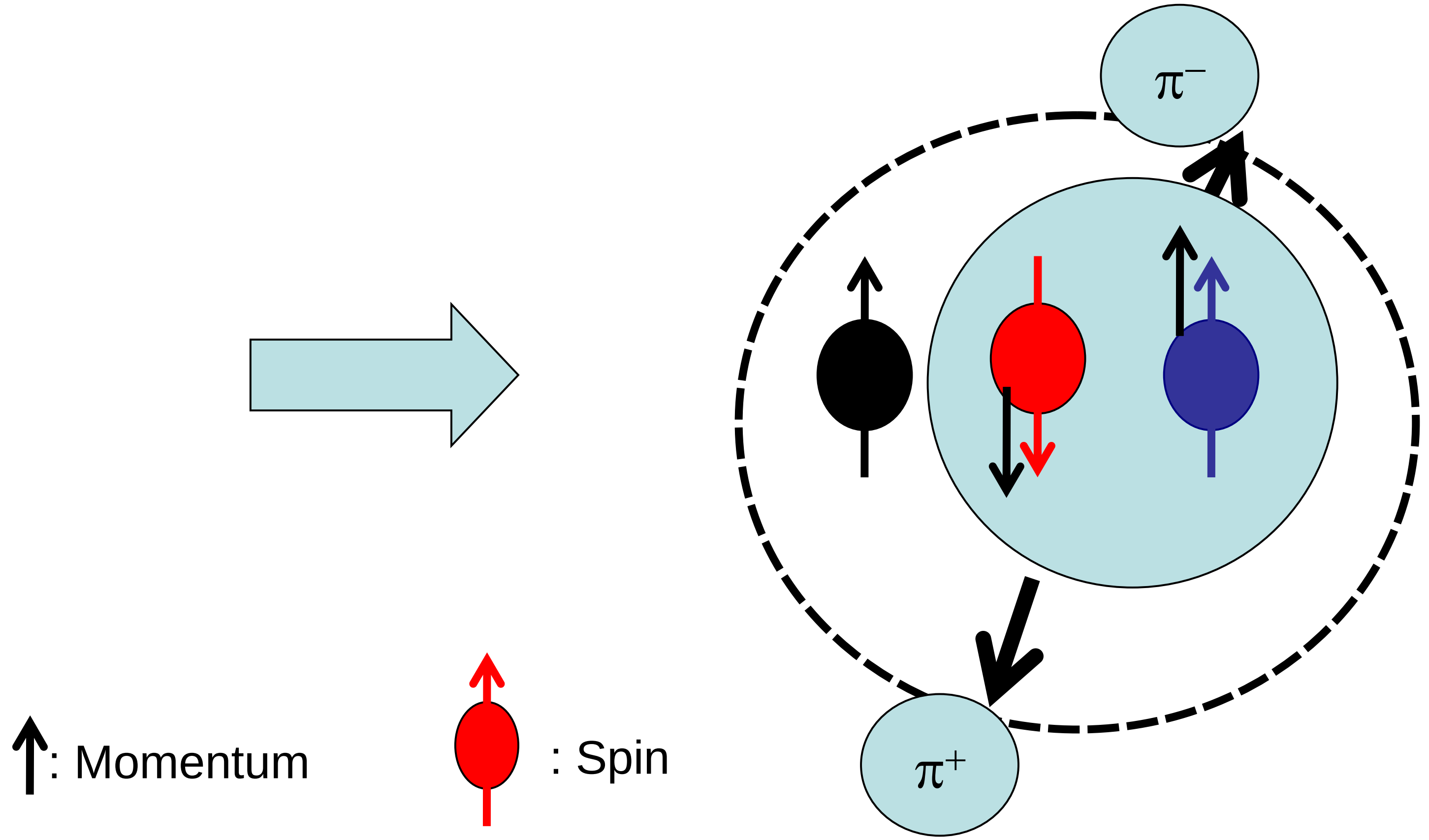


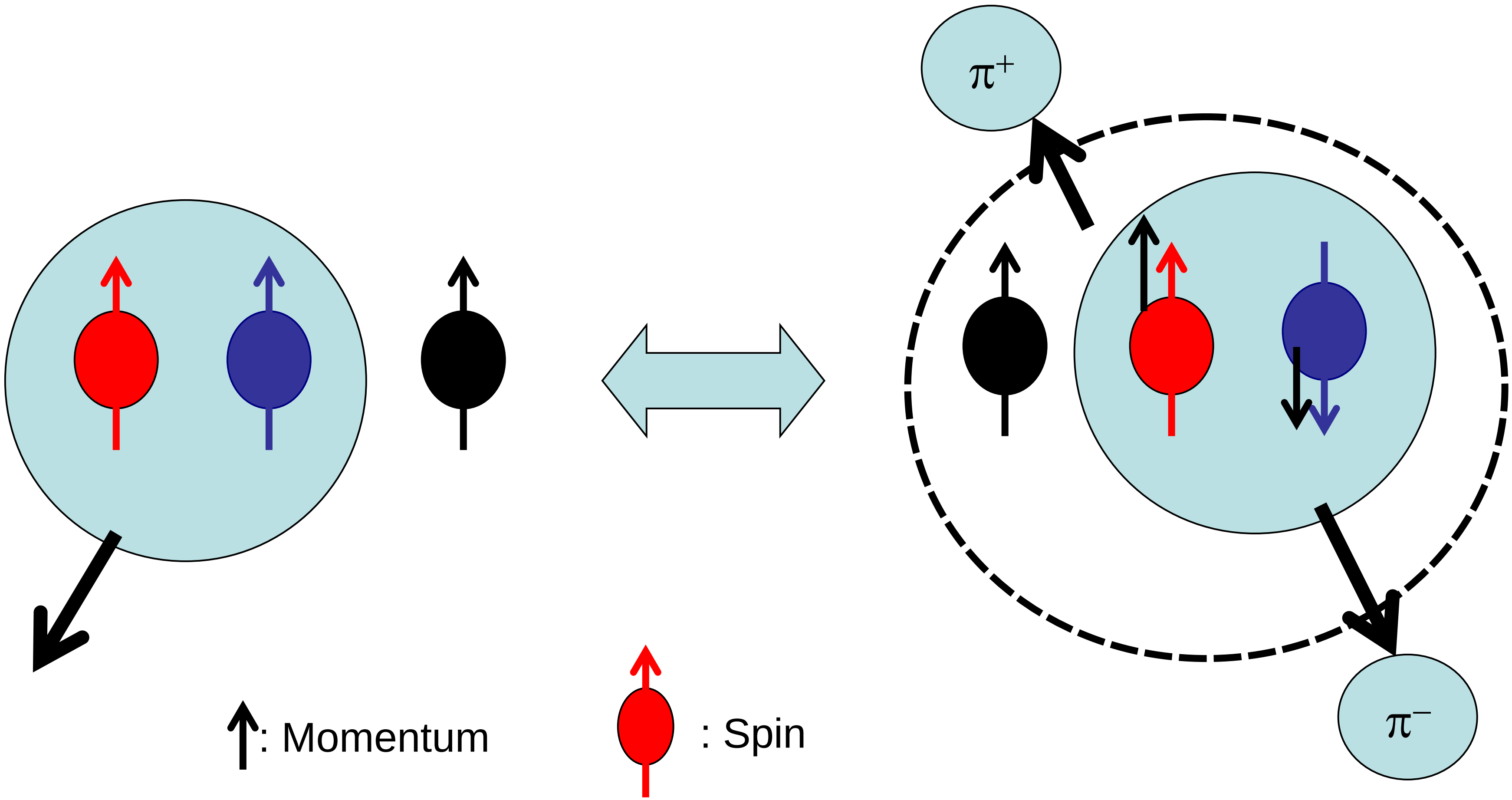
$z_{1,2}$ relative pion momenta

Fragmentation in P odd Bubbles leads to Azimuthal Asymmetries



- Fragmentation in P-odd bubble leads spin-momentum correlation
- Difference in ‘Winding number’ gives effective increment in chirality
- Spin alignment via chromomagnetic-electric effect
- Azimuthal event by event modulation
- Measurement: Extract width of distribution of first moments

Mix of P-odd FF with Collins FF leads to Event by Event Asymmetries



Coupling to Collins FF leads to $\sin(\phi_1+\phi_2)$ asymmetry

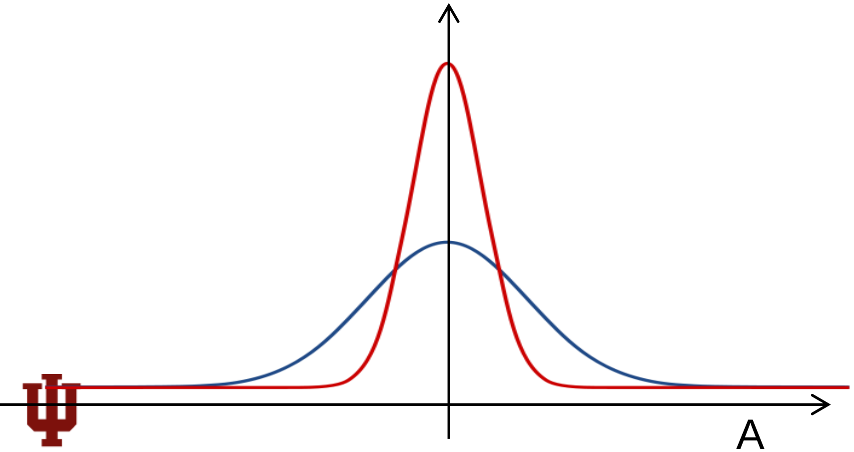
Compare to Collins x Collins ~ (P-odd FF) x (P-odd FF): $\cos(\phi_1+\phi_2)$

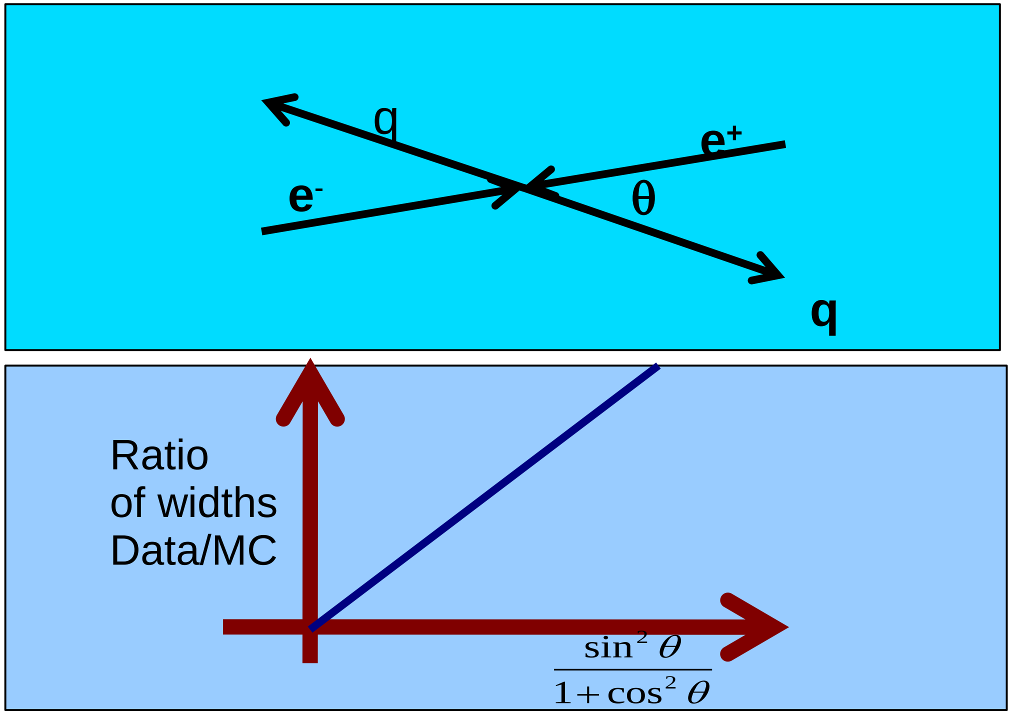
Averages out Event by Event since we do not know if quark or antiquark is in p-odd bubble

Kang, Kharzeev: Phys.Rev.Lett.106:042001,2011

Current Analysis

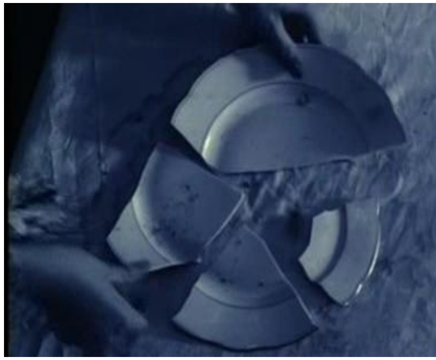
- Use unbinned maximum likelihood fit for each event ->extract asymmetry A
- Width of distribution of A is indication of effect
- Compare with simulation
- Physical effect has to have linear dependence on $\frac{\sin^2\theta}{1+\cos^2\theta}$ giving the transverse spin projection





Summary and Outlook

- Knowledge of fragmentation functions necessary to understand nucleon structure from semi inclusive measurements
- Belle measured transverse spin dependent di-hadron fragmentation function
- Results will allow for the first time extraction of transversity in proton-proton collisions
- Understand large transverse spin asymmetries
- Important step in understanding spin structure of the proton
- Other measurements underway:
    - Collins fragmentation function for Kaons
    - Polarized Lambda fragmentation functions
    - Unpolarized fragmentation functions (inclusive, di-hadron)
    - Rho fragmentation functions
- Fragmentation might be sensible to parity odd bubbles in the QCD vacuum
- First time observation of non-perturbative QCD effects induced by sphalerons, instantons
- Implications for early universe
- Necessary to understand effects observed in heavy ion collisions



Backup

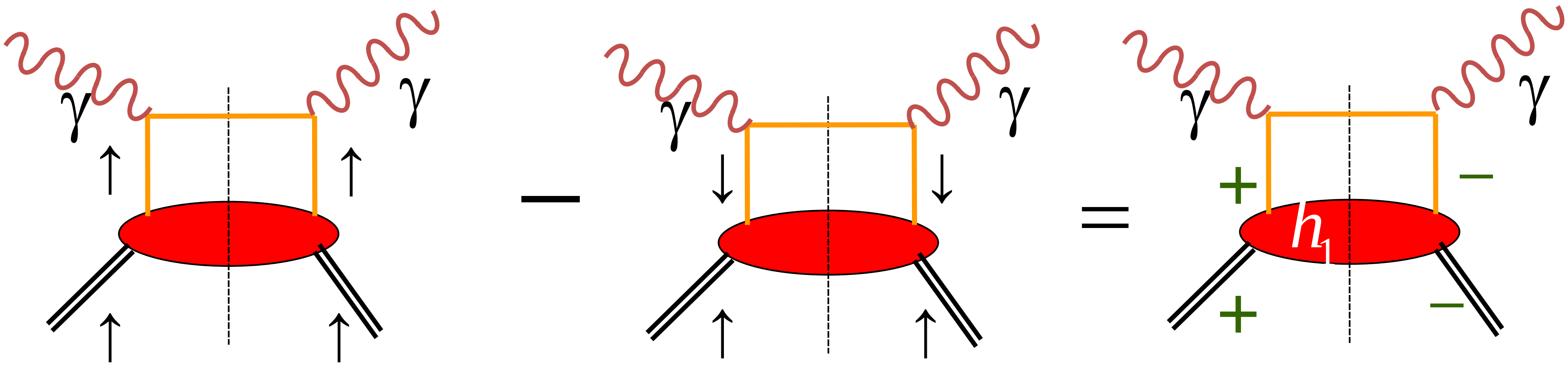
Systematic Errors

- Dominant:
  - MC asymmetry + its statistical error (up to % level)
- Smaller contributions:
  - mixed asymmetries: per mille level
  - higher moments: sub per mille level
  - axis smearing,
  - tau contribution
  - Charm contributions

- Possible Gluon radiation not accounted for

Transversity is Chiral Odd

- Transversity base:

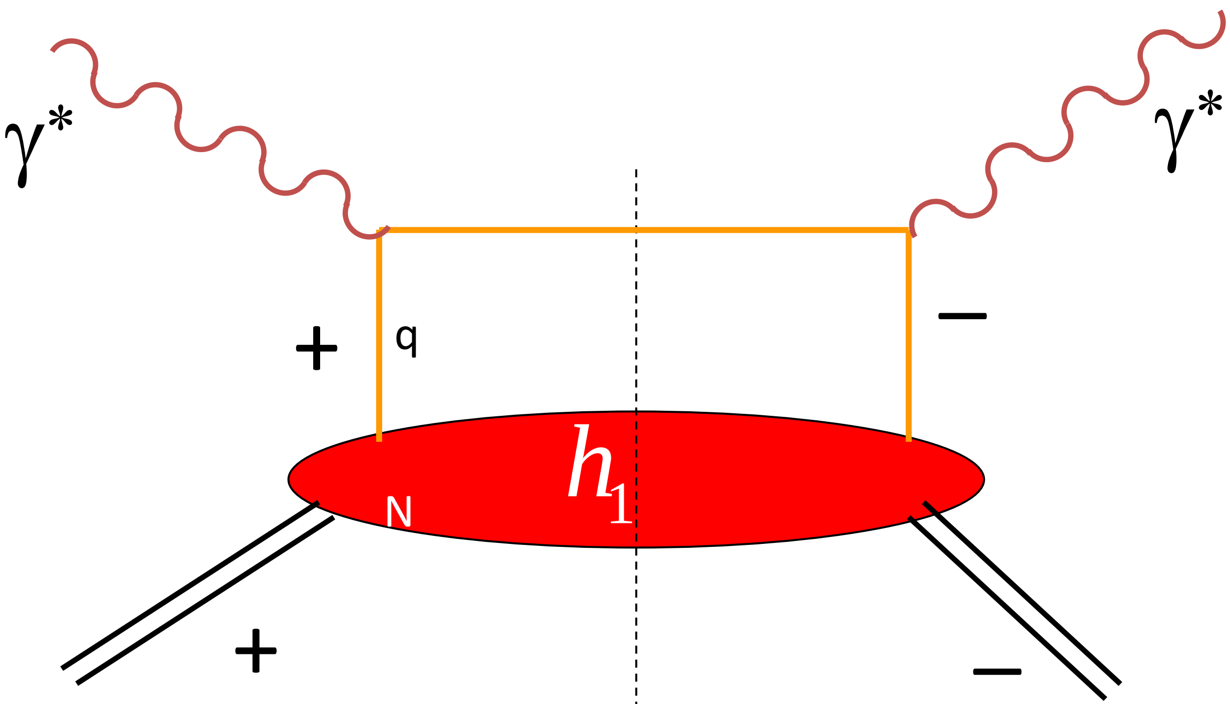


Difference in densities for ↑, ↓ quarks
in ↑ nucleon

- **Helicity base**: chiral odd

Need chiral odd partner => Fragmentation function

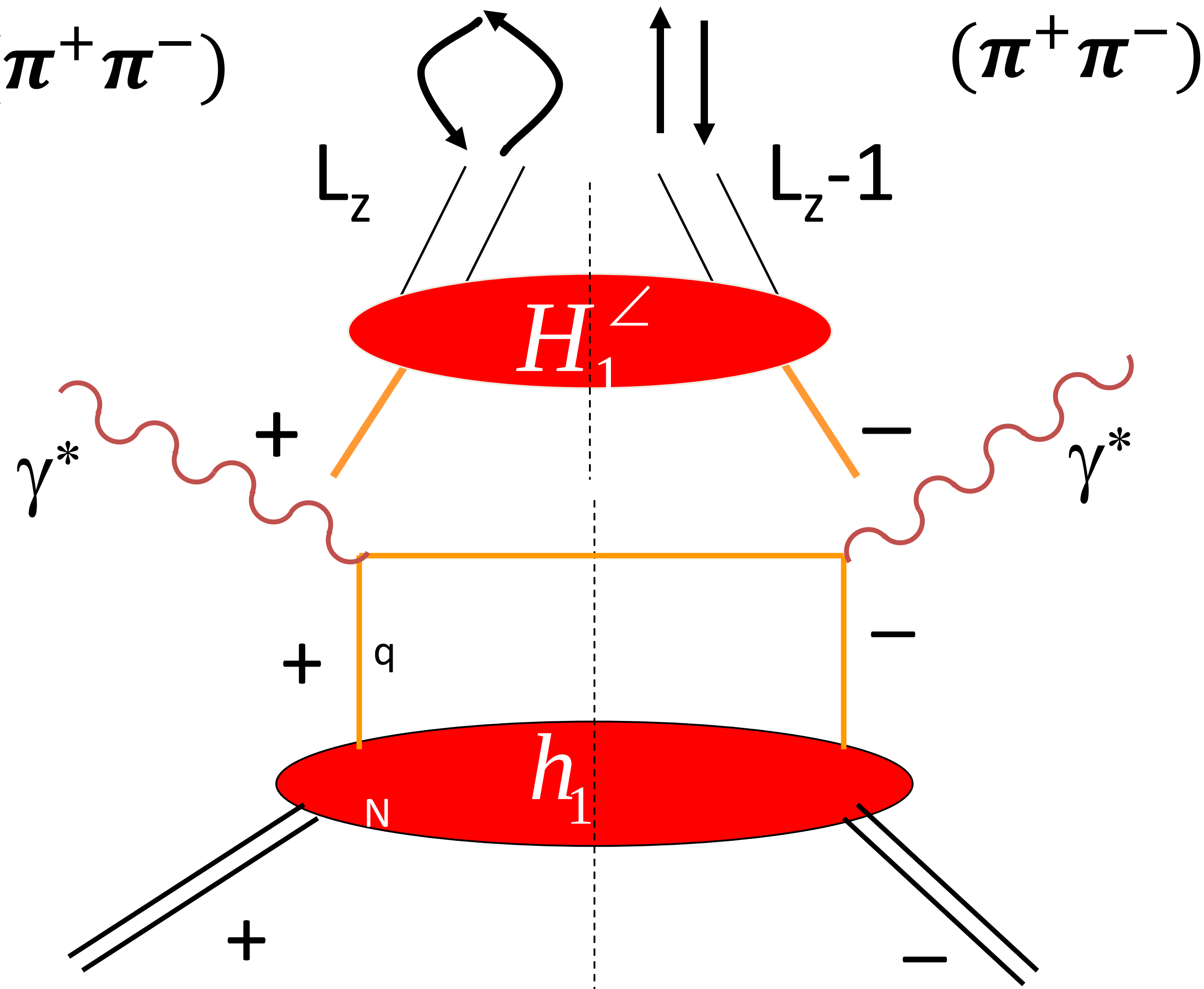
Chiral odd FFs



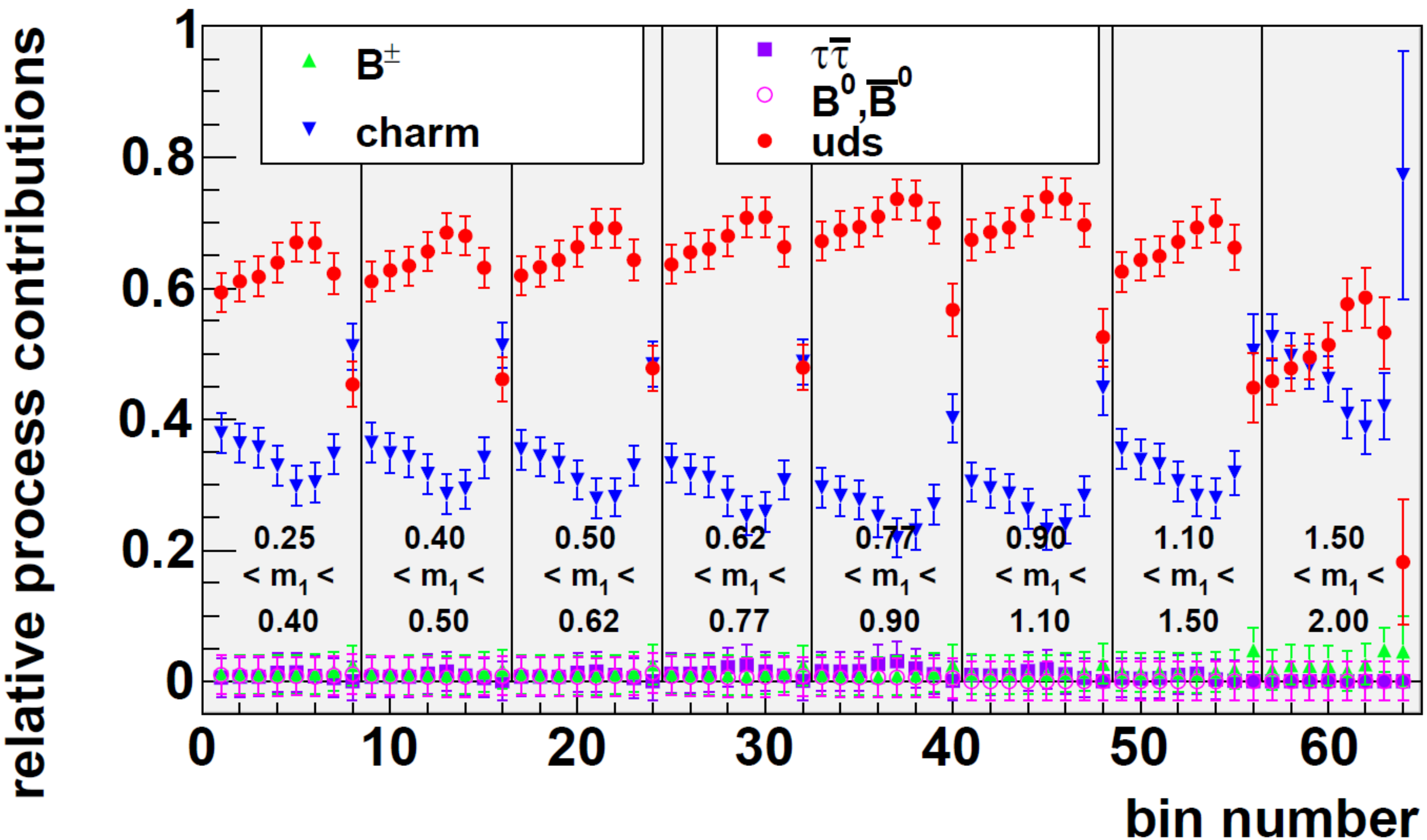
Chiral odd FFs

Interference Fragmentation Function

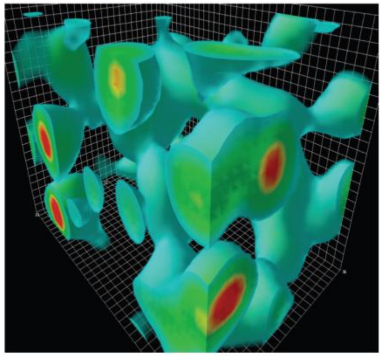
$\rho \rightarrow (\pi^+\pi^-)$



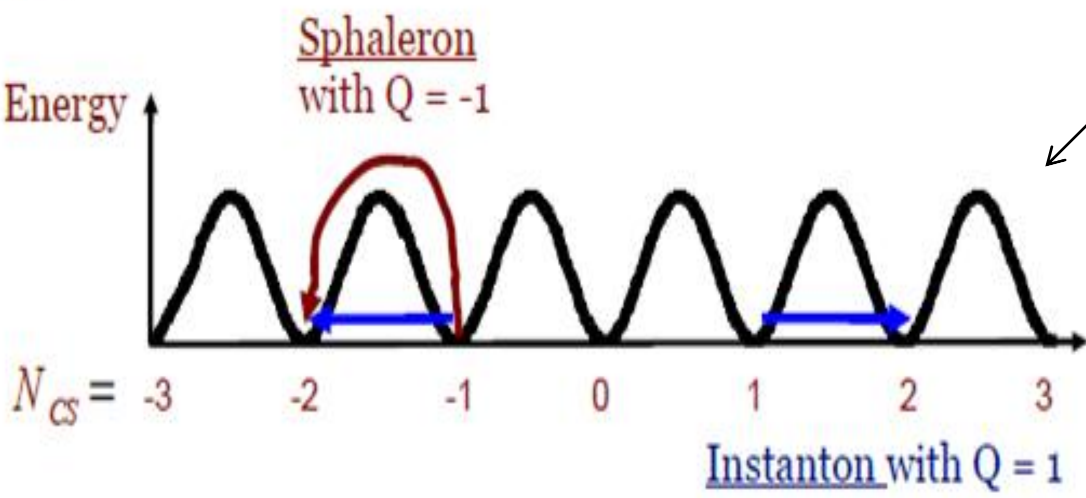
Subprocess contributions (MC)



Transitions in the QCD vacuum carry net chirality



The QCD Vacuum

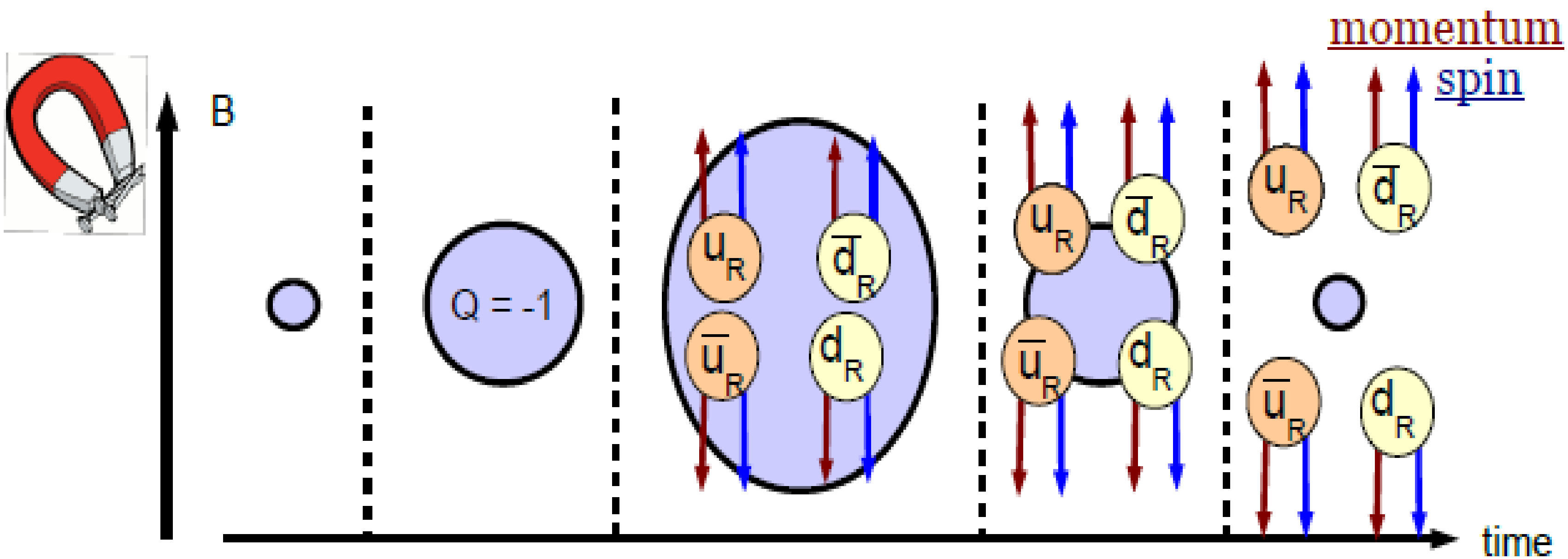


Difference in winding num
Net chirality carried by
Instanton/Sphaleron

- Vacuum states are characterized by “winding number”
- Transition amplitudes: Gluon configurations, carry net chirality
- e.g. quarks: net spin momentum alignment

Picture: H. Warringa,

Chiral Magnetic Effect leads to Charge Separation



Kharzeev, McLerran and Warringa, arXiv:0711.0950,
Fukushima, Kharzeev and Warringa, arXiv:0808.3382

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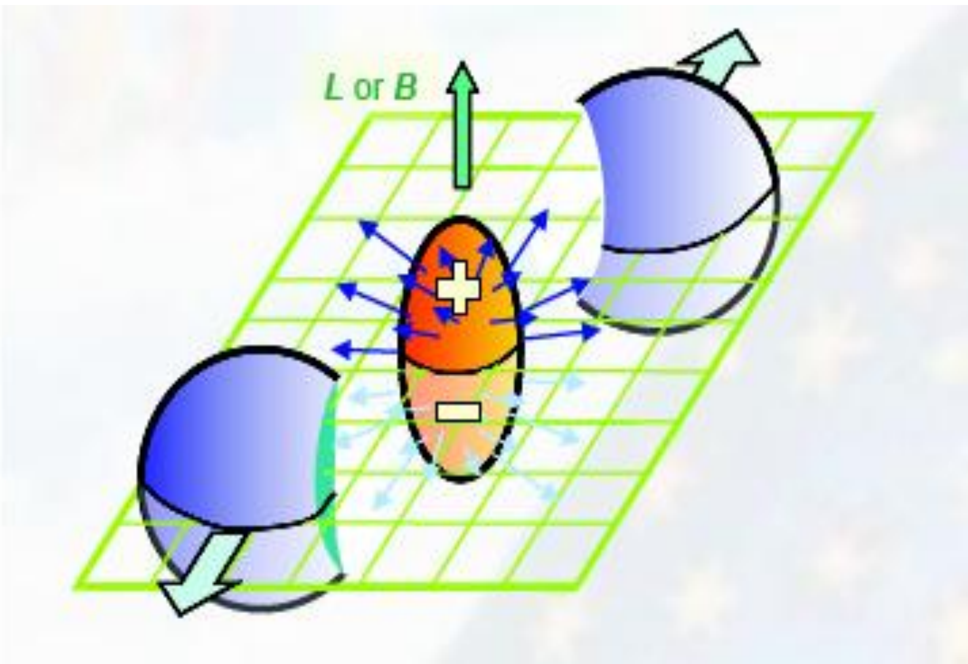
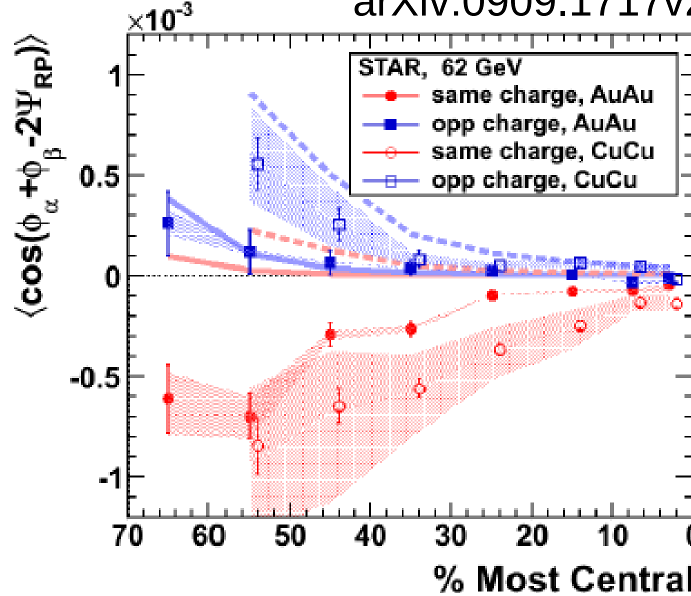


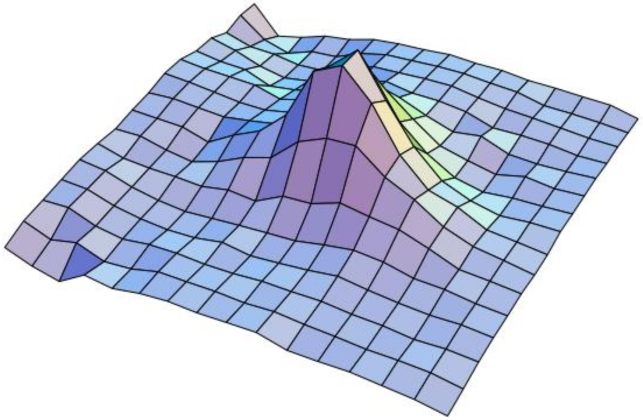
arXiv:0909.1717v2 [



- In Heavy Ion Collisions charged particle correlations agree with expectations from p-odd bubbles
- But: can also be explained by other dynamical effects in the quark gluon plasma
- B approx 10^{18} G

Significance

- Access to QCD vacuum structure
- First observation of Sphaleron/Instanton induced processes: non-perturbative topological objects
- In EW sector similar transitions are needed for Baryogenesis



- Need independent probe!

Upgrade to

- Belle II is a significant upgrade to Belle and will sample 2 orders of magnitude higher luminosity

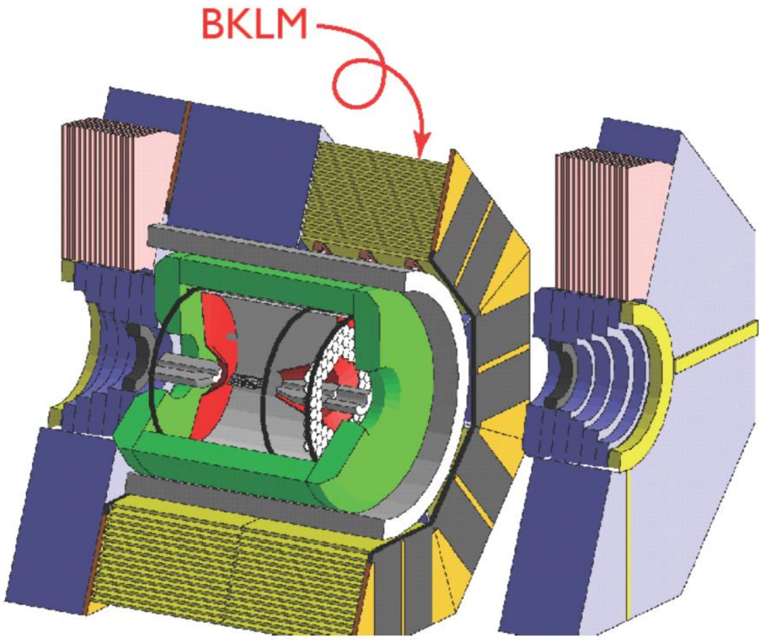
- High precision data will enable measurement of

  - P-odd FFs

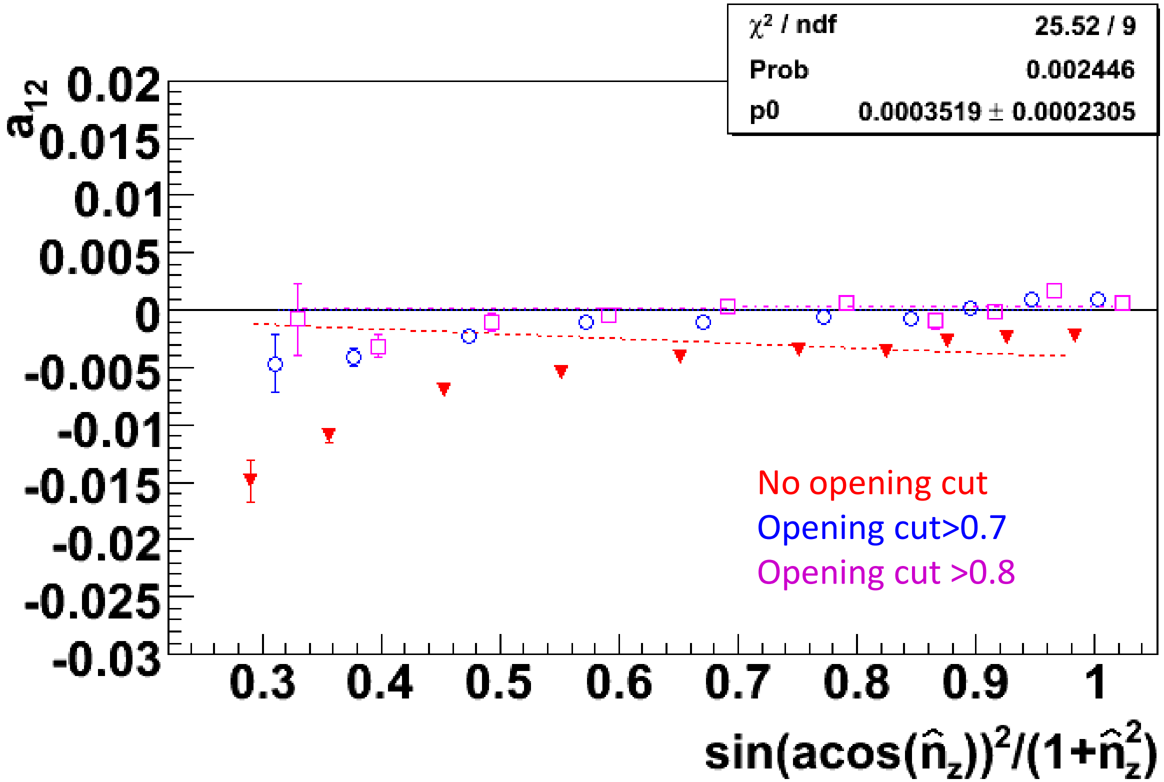
  - Transverse momentum dependent FFs

  - Charm suppression possible

- IU develops FEE for Barrel KLM detector crucial for high precision FF measurement of identified particles



Zero tests: MC



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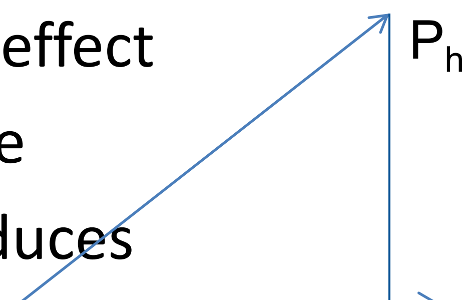
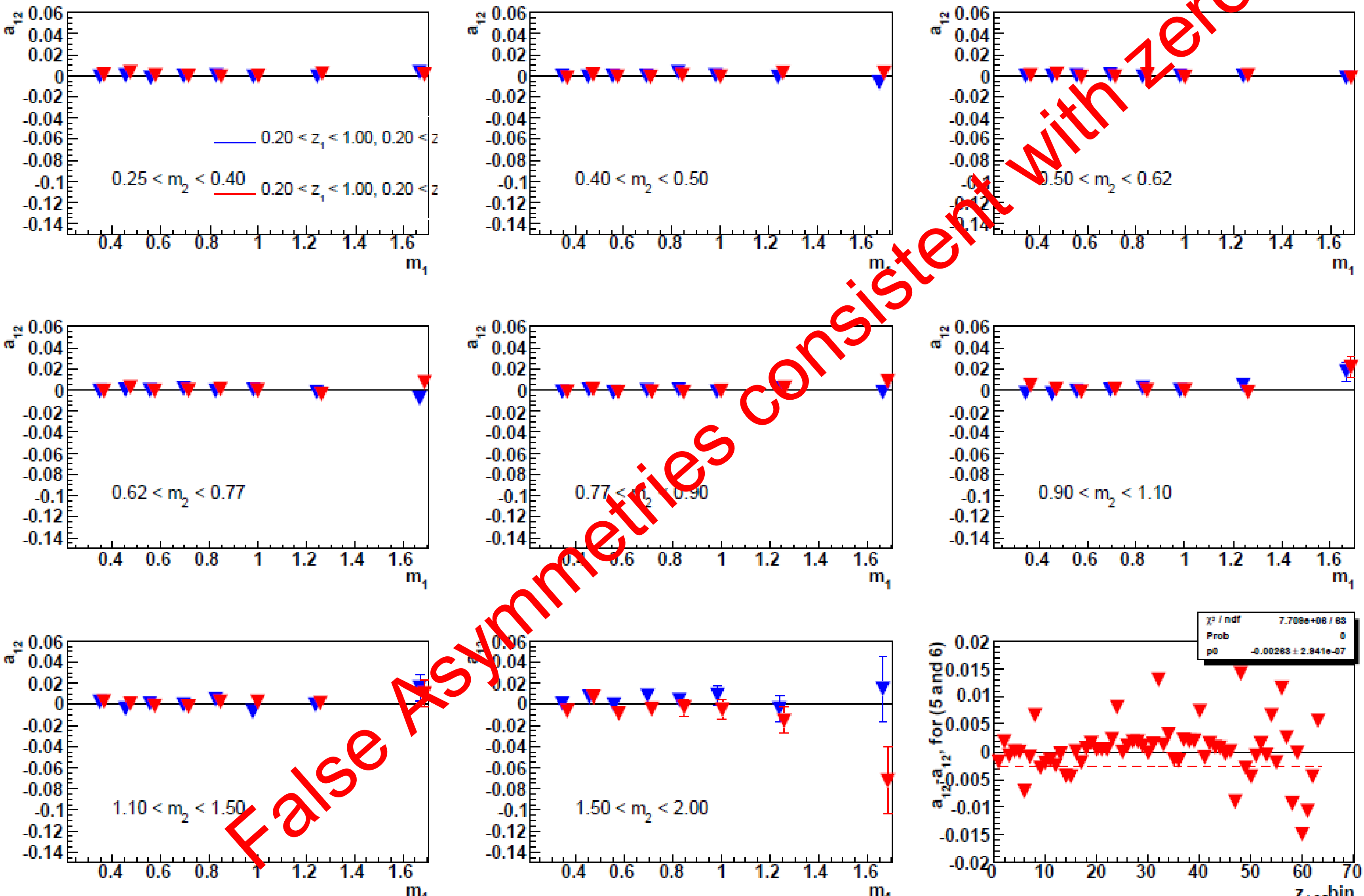
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level



$$\frac{P_h \bullet \hat{n}}{|P_h|} = \cos(P, n)$$

43

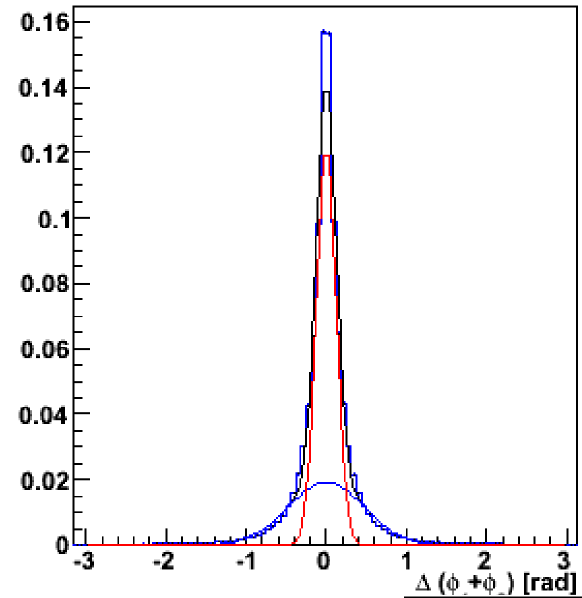
Zero tests: Mixed Events



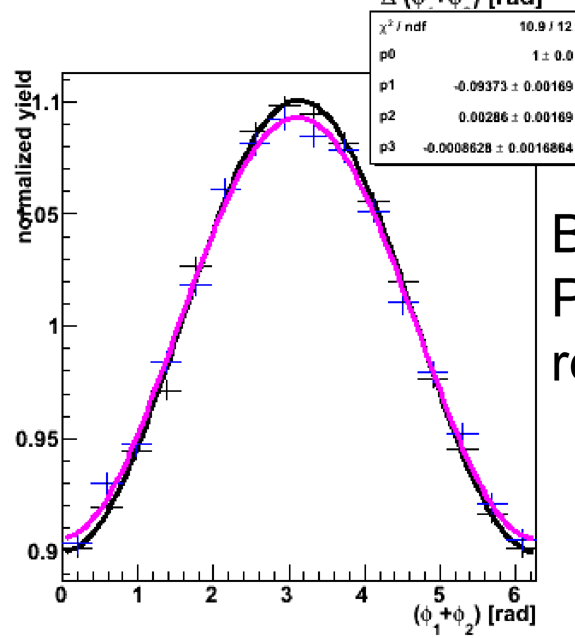
False Asymmetries consistent with zero

Weighted MC asymmetries

- Inject asymmetries in Monte Carlo
- Reconstruction smears thrust axis,
- ~94% of input asymmetry is reconstructed
- (Integrated over thrust axis: 98%)
- Effect is understood, can be reproduced in Toy MC
- Asymmetries corrected

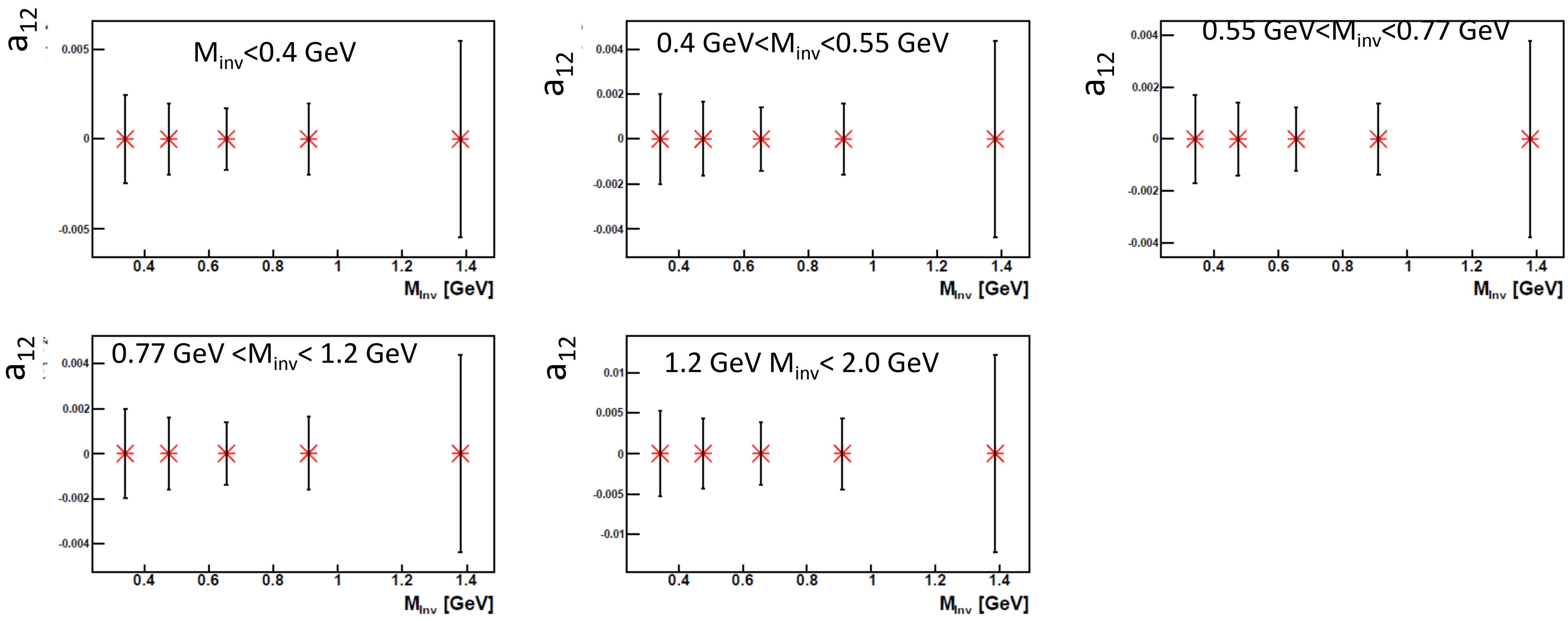


Smearing
In azimuthal
Angle of
thrust
Axis in CMS

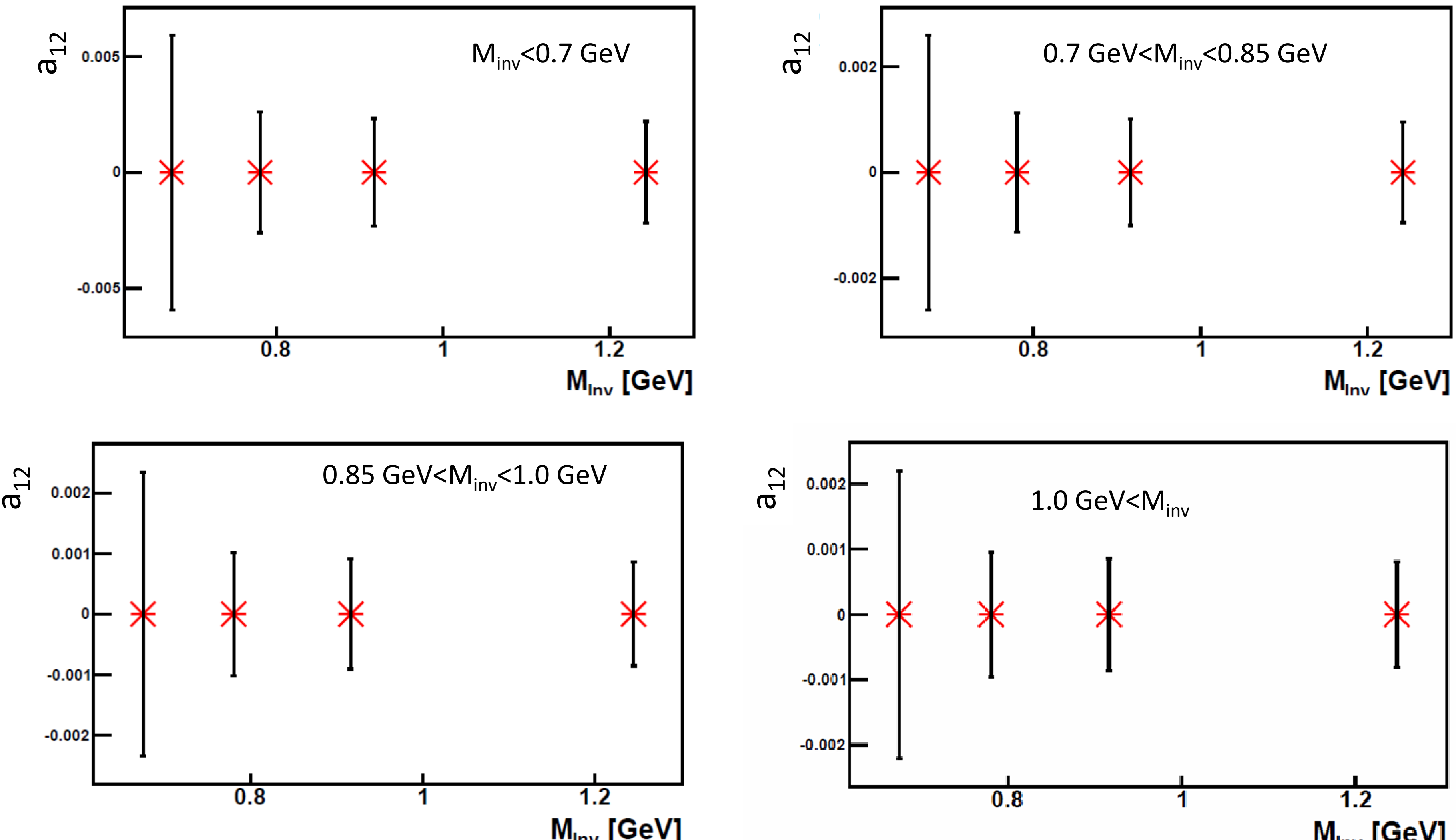


Black: injected
Purple
reconstructed

Projections for $(\pi^+\pi^0)$ $(\pi^+\pi^0)$ for 580 fb^{-1}



Projections for (π^+K^-) $(K^+\pi^-)$ for 580 fb^{-1}



Summary

- First measurement of Interference Fragmentation Function!
- Asymmetry significant
- Combined Analysis of Di-hadron and single hadron measurements possible
- Systematic effects to be finalized
- Future goal: Combined analysis of SIDIS, pp, e^+e^- data
  - Extract transversity
  - Disentangle contributions to A_N

$\vec{k}$:quark momentum

$\vec{s}_q$:quark spin

$\vec{R}$:momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$

$\vec{R}_T$:transverse hadron momentum difference

$$z_{\text{pair}} = E_{pair} / E_q$$

$$= 2 E_{pair} / \sqrt{s}$$: relative hadron pair momentum

Outlook

- Near future
  - IFF/Collins for more flavors
  - A lot of effort on precise measurements of unpolarized identified fragmentation functions, first results soon!
  - Unpolarized two hadron fragmentation functions
- Far future
  - Continue to measure precise spin dependent fragmentation functions at Belle
    - kT dependence of Collins function
    - Artru model test with Vector meson Collins

$\vec{k}$: quark momentum

$\vec{s}_q$:quark spin

$\vec{R}$: momentum difference $\vec{p}_{h1} - \vec{p}_{h2}$

$\vec{R}_T$: transverse hadron momentum difference

$z_{pair} = E_{pair}/E_q$

$=2E_{pair}/\sqrt{s}$: relative hadron pair momentum

m: hadron pair invariant mass